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Glacier National Park Stream Ecological Integrity

2007–2009 Status Report

Natural Resource Report NPS/ROMN/NRR—2018/1699





ON THIS PAGE
Rocky Mountain Network stream crews collect water quality data from a tributary to Bowman Lake, Glacier National Park, 2008.
Photograph by: E. Sexton (Flathead Lake Biological Station)

ON THE COVER
Jennifer Asebrook (Glacier National Park) samples a site on Reynolds Creek, Glacier National Park, 2010.
Photograph by: J. Hintz (Glacier National Park)

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The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

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Executive Summary

Background

Glacier National Park (hereafter, Glacier) has some of the cleanest water in the world. Its streams and rivers are treasured for their beauty, pristine condition, and high levels of ecological integrity. Their biological distinctiveness is outstanding. The wealth of aquatic biodiversity they support includes over 500 taxa of diatoms (unicellular algae); endemic and threatened aquatic insects, such as the meltwater stonefly (*Lednia tumana*); amphibians; and six native salmonid fishes, including the threatened bull trout (*Salvelinus confluentus*) and the state-sensitive west slope cutthroat trout (*Oncorhynchus clarkii lewisi*). Streams and rivers are often what visitors come to see and what they remember when they leave; they have played an important role in the history and mythology of the region.

Streams are also one of the most threatened natural resource types worldwide – even in large wilderness parks like Glacier. Biologists estimate that statewide, 95% of Montana's waters are degraded, have lost native species, and/or have been invaded by exotics. Though rare in the park, human stressors driving these impacts include impoundments, diversions, channelizing, rip-rap, culverts, de-watering, and pollution, as well as direct impacts from human users of stream resources, such as dispersing exotic species, starting fires that affect riparian cover and sediment input, and impacting wildlife. Cumulative impacts from larger scale disturbances, such as forestry, mining, air pollution, and climate change are also important added threats that do not recognize boundaries of protected areas like Glacier.

Because streams and rivers depend on inputs of energy and nutrients from the surrounding landscape, they are excellent indicators of Glacier's overall ecological condition. The National Park Service Rocky Mountain Inventory and Monitoring Network (hereafter, network) has selected a suite of stream ecological condition indicators that provide long-term ecological monitoring data and information to park managers. Traditional stream monitoring approaches focus on large changes in water chemistry or hydrologic regime, which in general do not occur in the park (note that this would change if glacier-driven hydrologic regimes switch to snowpack driven ones). Rather, network monitoring is based on the premise that understanding and managing the streams and rivers in the park is best accomplished by treating them as complete hydrologic systems. These hydrologic systems, when in good condition, support a balanced, integrated, and adaptive community of organisms, with a species composition, diversity, and functional organization comparable to that of the highest quality natural habitats of the region. To accomplish this, we use an integrated approach called bioassessment. While regulatory considerations provide an important context for stream monitoring in Glacier, our emphasis on long-term ecological integrity is a key distinction from stream monitoring conducted by the state, other federal agencies, or tribal nations.

This report presents results of network Stream Ecological Integrity (SEI) monitoring within the streams and rivers of Glacier from 2007 to 2009. A separate future report provides trend results from intensive monitoring over a decade at four sentinel sites. We focus here on condition estimates for the population of sampleable streams in the park. Our approach is unique in two ways. First, we generate statistically valid estimates that are applicable with known confidence to the entirety of the stream resource in the park. Second, we develop and emphasize estimates of synthetic ecological integrity using both existing and custom, park-scaled bioassessment models of aquatic biota.

Navigating the report for different audiences

This report provides both high-level summaries and comprehensive detail to meet the needs of its two primary audiences: park resource managers and network scientists. Managers needing a concise overview of results can read the summary condition tables in the Executive Summary and Results sections. Details are available in the narrative and appendices to provide in-depth context and methodological guidance.

Methods

SEI methods are documented in the *Rocky Mountain Network Stream Ecological Integrity Monitoring Protocol*. They are derived from well-established and existing methods developed by network partners. The application of a standardized monitoring protocol facilitates comparison of the park's streams and rivers to those within the same ecoregions as the park.

From 2007 to 2009 we sampled 40 stream sites selected from across the park using a random survey design that provides a statistically valid estimate of stream conditions for the park as a whole. In addition, we sampled six "gradient" sites selected subjectively to provide information on stream conditions at heavily disturbed or especially pristine sites. We also surveyed four "sentinel" streams three or four times annually to provide an indication of how stream conditions change over time (the annual monitoring will be reported

separately from this survey report). Overall we conducted 75 sample events that included all methods at these sites during the three year period presented in this report. An additional 14 sample events that did not include all methods (i.e., only water chemistry was sampled) were completed over these years. Section 2.1 provides more details and maps of all sample sites and Appendix A contains a map of all sites.

The SEI protocol includes a broad spectrum of indicators to help evaluate the ecological integrity of the streams and rivers of Glacier. We include measures of both drivers and stressors and ecological responses such that we better understand the linkages between these and help parks apply these relationships to resource management. Core indicators include multiple measures of water and sediment chemistry (i.e., nutrients, metals, temperature); physical habitat (i.e., substrate composition, riparian cover, channel geomorphology); and community level assays of two important biological communities: macroinvertebrates and algae. The latter provide an integrated aspect for assessing ecological integrity because these organisms respond to environmental conditions over time and space.

By design, we do not include fish as a vital sign in SEI monitoring for several reasons. First, National Park Service Inventory and Monitoring Division guidance directed networks to complement and not duplicate existing monitoring programs. Glacier, Montana Department of Fish, Wildlife and Parks, and other partners were already monitoring fish populations (especially threatened bull trout, and invasives, such as lake trout (*Salvelinus namaycush*)). Second, in headwater systems such as Glacier, low fish diversity means it is challenging to understand how fish communities respond to ecological conditions. Finally, monitoring fish communities and populations adequately requires staff expertise, time and equipment that the network cannot afford. However, and also by design, network stream monitoring aims to complement existing fish inventory and monitoring programs by providing detailed information on a wide range of fish habitat conditions, including information on the algae and aquatic insect communities that support fish.

A key element of SEI monitoring is the interpretation of results in a way that is both scientifically defensible and relevant to the management of Glacier's streams. In broad stroke, we compare our monitoring results to numeric "assessment points" that establish boundaries between different classes of disturbance or ecological condition. These assessment points are based on management guidance, regulatory criteria, reference sites in the park and/or its surrounding ecoregions, and well-defined ecological thresholds. We interpret comparisons between SEI data and these assessment points in a collaborative way with park staff and management in the context of park management objectives, National Park Service I&M Division guidance, National Park Service resource management policies, and general ecological theory.

Components of stream ecological integrity

Human disturbance

One of the foundations of SEI monitoring is the estimation of human disturbance(s) that impact Glacier's streams and potentially degrade ecological integrity. We use a Human Disturbance Index (HDI) to quantify a catchment-scale and suite of reach-scale human stressors at each monitoring site. These stressors include roads and trails, structures, and land cover and land uses, such as landfill, agriculture, mining, and logging. We classify HDI at each site into four disturbance classes: negligible, minor, moderate, and major. These disturbance classes are connected to four ecological condition classes (via modeling): pristine reference condition, reference condition, intermediate condition, and non-reference condition, respectively.

Water chemistry

Water chemistry (often described with the more general term "water quality") is a key aspect of stream habitat. It is also a common focus of most long-term stream monitoring programs, especially for regulatory purposes under the Clean Water Act. Water chemistry includes parameters analyzed *in situ*: dissolved oxygen, pH, specific conductance, and water temperature sampled with probes. We also include parameters measured in the lab: nutrients, metals, sediments, and major ions.

Physical habitat

Physical habitat is an important control on ecological processes and ecological integrity in Glacier's streams. Physical habitat of streams includes stream channel dimensions and patterns (e.g., width and depth, ratio of riffles to pools, gradient), sediment characteristics (the size and types of sediments that make up the streambed), amount and type of wood in the stream, stream flow, and the amount and type of vegetation in the riparian zone and catchment overall. These characteristics influence habitat volume, complexity, interaction with the floodplain, and other important determinants of the species and distribution of plants and animals that live in and near the stream. Stream physical habitat, especially sediment levels and stream morphology, like pool depth, can be affected by human disturbances.

We include the presence of invasive/exotic plants as an important measure of physical habitat. Understanding and monitoring invasive/exotic taxa in riparian systems is key for Glacier resource management. Invasive/exotic riparian taxa have been associated with multiple negative effects, including 1) alteration of fire, nutrient, or hydrologic regimes; 2) changes to patterns in carbon sequestration; and 3) changes to plant and animal distributions.

Bioassessment of ecological integrity

Macroinvertebrates and diatoms are major components of the biodiversity found in streams. They are the base of the food web and thus support a broad range of other species. They are useful and efficient indicators of ecological integrity because of their ability to integrate different processes and because they respond to physical, chemical, and biological disturbances at multiple temporal and spatial scales. The diversity of Glacier's macroinvertebrate and diatom communities is exceptionally high, with a continentally outstanding biological distinctiveness. As just one example, research by the network and our partners has led to the identification of 46 new-to-science diatom species, 30 of which have their type locality in the park.

Because the National Park Service is responsible for protecting and managing ecosystems (e.g., streams), which are usually complex and include many species, our stream monitoring at Glacier is multifaceted. It includes multiple indicators and focuses on the interpretation of synthetic and integrative bioassessment models of macroinvertebrate and diatom community structure as indicators of ecological integrity. We consider our models of macroinvertebrate and diatom community condition, along with established methods used by Montana Department of Environmental Quality, to be our best evidence (compared to other information, such as from water chemistry or stream physical habitat) for the ecological integrity of Glacier's streams.

We also assess macroinvertebrate and diatom communities in relation to specific aspects of human disturbance, such as nutrient concentrations, metals, fine sediments, or water temperature. However, these are complicated relationships, especially in a landscape like Glacier where many natural drivers also strongly structure these communities.

Aquatic invasive/exotic species

Aquatic invasive/exotic species can have a strong effect on stream ecological integrity and are a focus of park resource management. We surveyed for zebra mussel (*Dreissena polymorpha*) and quagga mussel (*Dreissena rostriformis bugensis*), rusty crayfish (*Faxonius rusticus*), and New Zealand mudsnails (*Potamopyrgus antipodarum*). We also recorded presence of the invasive but native diatom "rock snot" (*Didymosphenia geminata*). Rock snot can form extensive mats, inhibiting the growth of other algal species, changing the composition of aquatic communities, decreasing suitable spawning habitat for fish, changing in-stream chemistry, and lowering the aesthetic appeal of streams.

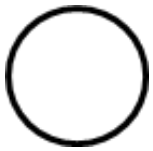
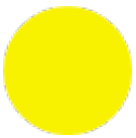
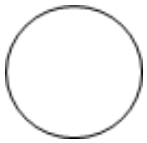
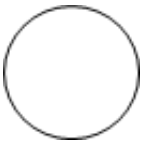
Results and interpretation

Overall, the ecological integrity of the majority of the streams and rivers in Glacier was in reference or pristine reference condition in 2007–2009. Macroinvertebrate and diatom communities were largely intact and sometimes included previously undescribed species, suggesting a high level of biological distinctiveness. Localized impacts from sediments, nutrients, or metals were minor. Front country streams, including select tributaries to the North Fork of the Flathead (Coal Creek, Big Creek, anc Canyon Creek) Rubideau Creek near park headquarters, Divide Creek near St. Mary, and Railroad Creek near East Glacier had relatively reduced ecological condition, potentially driven by human disturbance.

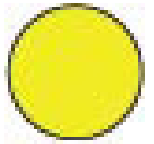
Summary condition table

Summaries of results are presented in the following "summary condition table." Complete results and interpretation are provided in the report's main text. The summary condition table includes an overview of the indicators in a category, a brief description of results, and a graphic that encapsulates the overall status for the category and our confidence in our interpretation. The overall condition graphical summaries (i.e., a green dot for an indicator in reference condition) are based on the data in this report as compared to assessment points. However, because many indicators have complex relationships with assessment points, and to simplify the evaluations, we combine indicators in a category. Thus, we are sometimes generalizing across multiple indicators, where one may be in a reference state and another may not. We use our best professional judgement to assign an overall condition to a category of indicators, and these should be interpreted with some caution.

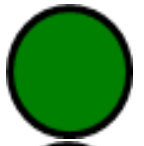
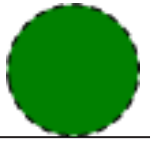
Symbology and terminology for summary condition tables.

Condition status		Confidence in assessment	
Symbol	**Description**	**Symbol**	**Description**
	Non-reference condition Major disturbance		High
	Intermediate condition Moderate disturbance		Medium
	Reference condition Minor disturbance		Low
	Pristine reference condition Negligible disturbance	–	–
	Unknown or indeterminate condition	–	–

Summary condition table for indicators of stream ecological integrity (SEI) monitored at Glacier National Park from 2007 to 2009. Note that more detailed summary condition tables are given in each major results section.

Component of SEI	Indicator	Condition description	Condition and confidence
HUMAN DISTURBANCE	Human disturbance	In 2007–2009 there was a strong gradient in human disturbance across streams in the park. Almost 60% of the streams in the park were in a negligible disturbance class with no evidence of human disturbance at the reach scale and no roads intersecting the stream network in a site's catchment. Around 17% and 16% of the stream sites in the park were in minor and moderate human disturbance classes, respectively. These sites were often near minor front country facilities or less traveled road corridors. They often had some near-channel human land use. Finally, about 11% of streams in the park were in a major human disturbance class. These were located near primary visitor service facilities and/or paved and well-traveled road corridors. In the bioassessment sections of this report, we link human disturbance to biological response and show that the majority of the park's negligibly disturbed streams are in a reference condition, with high ecological integrity. We suggest that the majority of the park's streams are secure and that this is generally not an important area of concern for the park. Models of human disturbance confirmed the importance of roads and structures in elevating human disturbance. Several natural gradients, such as elevation and geographic location in the park, also covaried with human disturbance. We have high confidence in our overall assessment. *Our models showed that longer term and larger scale disturbances, such as minimum summertime stream water temperatures also positively varied with human disturbance. This might be suggestive of potentially troublesome interactions between climate change driven increases in a key stream ecological attribute (water temperature) and levels of proximate human use in and near the park's streams.*	
WATER CHEMISTRY	Overall water chemistry	Overall water chemistry in Glacier in 2007–2009 showed little cause for concern. Streams in a few areas (front country below lower Lake MacDonald Creek and Railroad Creek near East Glacier) showed some minor water chemistry issues as discussed below. However, without additional research, we cannot connect these water chemistry issues with a meaningful ecological response. Overall we have medium to high confidence in our assessment for these parameters.	
	in situ parameters	*In situ* water chemistry, such as water temperature or pH at SEI survey sites, showed a fairly wide range, likely due to the high levels of diel and seasonal variation. Overall, in situ parameters in Glacier from 2007 to 2009 do not suggest high levels of human disturbance or problems in the park's streams. We have medium confidence in our assessment. *Note that because of the connections we and other collaborators have seen between stream water temperature, climate change and ecological response, we have given this class of responses an intermediate condition/moderate disturbance designation. Water temperature is very important in streams and is susceptible to climate change. Therefore, this is something to watch carefully into the future.*	
	Major ions and suspended sediment	We measured several major ions at our sites across the park. Most variation in these is driven by reactions with naturally occurring surficial geology and there is little regulatory context for these parameters. Overall, there is little evidence for problems with major ions in the park's streams. Sediment can have a direct impact on stream biota and can be associated with elevated levels of nutrients and metals. Most Glacier streams had low total suspended sediment values and were as sediment free as the best sites in the surrounding ecoregions. However, select sites, especially on larger rivers, such as the North Fork of the Flathead, had some excess total suspended sediment and associated bed sediments. These are likely mostly from natural sources, but, given some development in the North Fork basin, this should be watched carefully. While more work is needed to better understand these patterns, it's likely that they have a relatively small localized effect on stream condition. We have high confidence in our assessment of major ions and suspended sediment.	
	Nutrients	We measured multiple nutrients (nitrogen, phosphorous, and carbon) at our sites across the park. Overall, there were few clearly human caused nutrient issues in the park's streams from 2007 to 2009. A small (12-13%) percentage of the park's streams had high (relative to Montana Department of Environmental Quality ecoregion specific criteria) nutrient concentrations in late summer. However, we expect this is mostly due to natural sources (i.e., nutrient rich alluvial floodplain groundwater upwelling zones or wetlands). We have medium confidence in our assessment of nutrients. *Of special note, exploratory models suggested that hydrology (i.e., stream flow) was important in influencing nutrient levels. Because hydrologic regime in streams is connected to climate change this could have important indirect and complex implications and is something to watch carefully into the future.*	

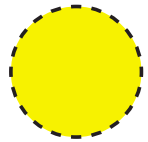
Summary condition table (*continued*) for indicators of stream ecological integrity (SEI) monitored at Glacier National Park from 2007 to 2009. Note that more detailed summary condition tables are given in each major results section.

Component of SEI	Indicator	Condition description	Condition and confidence
WATER CHEMISTRY (continued)	Metals	Metal levels in the streams of Glacier were of little concern. Very few sites had detectable concentrations and no median values were above any assessment point. Low metal concentrations are not unexpected given the neutral to basic pH of most water in the park and the lack of mining or urban sources. There is usually also a strong seasonal effect in the concentrations of metals, with peaks during runoff reflecting greater sediment transport. We report on temporal patterns in metals in a future SEI sentinel report. We have high confidence in our assessment for metals.	
PHYSICAL HABITAT	Overall stream physical habitat	Overall, stream physical habitat was mostly intact in 2007–2009, with nearly all indicators suggesting the majority of the park's streams were in a minor disturbance class. Front country streams below Lake MacDonald, Divide Creek near St. Mary, and Railroad Creek near East Glacier showed some minor sediment and pool habitat volume issues with potential connections to a human disturbance cause. Invasive/exotic plants were also found at several sample sites, but again mostly in the front country. We have high confidence in our assessment of physical habitat.	
	Volume	Habitat volume, or the amount of in-channel habitat available to stream biota, is an important determinant of the ecological condition of streams in the park. We focus on an indicator of residual pool depth (measured as the deepest point of a pool relative to the height of the downstream riffle crest). Our results suggest that most streams in Glacier had as much or more habitat volume as reference sites in the surrounding ecoregions. Exploratory models suggested that select sites, such as Rubideau and Railroad Creek, and the western tributaries to the North Fork of the Flathead (Coal and Big Creek) had less habitat volume than expected. Because these sites also had more human disturbance, this should be investigated more thoroughly and watched carefully. We have high confidence in our assessment.	
	Complexity	Our results suggest that most of the streams in Glacier have more complex habitat structure than reference sites in the surrounding ecoregions. Moreover there is sufficient large wood to support properly functioning salmonid habitat in nearly all of the park's streams. We have high confidence in our assessment.	
	Cover	Another key function of stream physical habitat is support of aquatic biota by providing cover for protection from predators or as spawning habitat (among many other functions). Our results suggest that most of the streams in Glacier have as much or more cover provided by natural features than reference sites in the surrounding ecoregions. Algal cover is comparable to ecoregional reference sites (note that too much algal cover could be from human caused nutrient enrichment). Pool density (a measure of the extent of an important habitat feature) was above a bull trout-based threshold in about 70% of the park's streams. We have high confidence in our assessment.	
	Sediment	We focus on a sediment indicator of bed stability that measures the tendency of streambed particles to resist transport under a given stream flow. Results suggest that most of the streams in Glacier have sediments comparable to ecoregional reference conditions. This should support properly functioning salmonid habitat and not adversely affect key macroinvertebrate species. Some sites, such as McDonald Creek next to the Going to the Sun Road, had more fine sediments than expected; however, models suggested that across all sites only 3% of the variation in bed stability was accounted for by human disturbance. Most sediment loads support properly functioning salmonid habitat and do not adversely affect key macroinvertebrate species. We have high confidence in our assessment.	
	Floodplain interaction	Our results suggest that most Glacier streams have reference level interactions with their floodplains based on incision, bankfull width to depth ratios, and bankfull width to wetted width ratios. Fewer of the park's stream reaches were as sinuous as in surrounding ecoregion reference sites. However many stream channels in the park are naturally confined due to steep topography or because they are larger rivers that meander at a scale beyond our sample reach. We believe that, in general, streams in Glacier have not been subjected to extensive human disturbances that have reduced sinuosity. We have low confidence in our assessment.	

Summary condition table (*continued*) for indicators of stream ecological integrity (SEI) monitored at Glacier National Park from 2007 to 2009. Note that more detailed summary condition tables are given in each major results section.

Component of SEI	Indicator	Condition description	Condition and confidence
PHYSICAL HABITAT (continued)	Hydrologic regime (habitat based)	About 70% of the park's streams had minor levels of disturbance to their hydrologic regimes from droughtiness (as indicated by the ratio of base summer flow to annual mean runoff), suggesting that drought risk is lower in most of the park's streams than in surrounding ecoregion reference sites. This is expected given the park's high elevation, high levels of precipitation, and minimal human modification (i.e., water diversion) that often increases drought risk. Likewise about 60% of the stream length in the park was less flashy (as indicated by the ratio of bankfull depth to wetted depth) than ecoregional reference sites. High flows with dramatic flooding can certainly happen in the park, but sites that tend to do this do not have any meaningful human disturbance that might cause this flashiness. Rather this likely reflects large watersheds that naturally store large volumes of water that can be released in high flows. We have medium confidence in our assessment. *Of note, the 13% of the park's streams with higher droughtiness (or that occurred in a major drought stress class) may be something to watch as climate change proceeds and the park's namesake glaciers disappear. For example, if combined with lower base flow habitat volume, impacts to stream biota from higher water temperatures and less glacial snow/ice melting in later summer from drought might be accentuated.*	
	Riparian vegetation	Results suggest that much of the stream length in Glacier has reference levels of riparian cover relative to ecoregional reference sites. Sites that lack cover do so largely due to natural patterns (i.e., they are in the alpine or are large rivers with extensive nonvegetated lateral bars). We have high confidence in our assessment.	
	Invasive/ exotic plants	Spotted knapweed (Centaurea maculosa) and Canada thistle (Cirsium arvense) were the most commonly recorded taxa, especially at sites like Railroad Creek tributary and Divide Creek, both of which are on the park's boundary and near roads. Around 62% of the park's streams were weed free or in a negligible stress class. We have high confidence in our assessment. However, we only documented simple presence/absence of 15 important invasive/exotic species, and our survey design does not target stream sites with high invasion probabilities. Therefore, this assessment should be used to understand long-term status of invasive plants across the streams of Glacier and not as a planning tool (e.g., for the exclusive identification of potential treatment areas or invasion "hot spots").	
BIOASSESSMENT	Overall stream ecological integrity	Based on an analysis of stream macroinvertebrate and diatom communities, the ecological integrity of Glacier's streams was mostly excellent, with the majority of the park's streams in a reference or pristine reference condition in 2007–2009. Macroinvertebrate and diatom communities were largely intact and sometimes included previously undescribed species, suggesting a high level of biological distinctiveness in the park. We consider our models of macroinvertebrate and diatom community condition, along with established methods used by Montana Department of Environmental Quality, our best evidence (compared to other information, such as from water chemistry or stream physical habitat) for the high integrity of the park's streams. Stressor-specific models of macroinvertebrate and diatom condition showed that localized impacts to these communities from sediments, nutrients, or metals were minor. Front country streams, including tributaries to the North Fork of the Flathead, Rubideau Creek near park headquarters, Divide Creek near St. Mary, and Railroad Creek near East Glacier were in worse condition, likely caused by human disturbance. We have medium to high confidence in our overall assessment. *There was some indication in our models that climate driven effects could negatively impact stream biota. Data from partners suggest this might be especially important for temperature sensitive species like the meltwater stonefly.*	

Summary condition table (*continued*) for indicators of stream ecological integrity (SEI) monitored at Glacier National Park from 2007 to 2009. Note that more detailed summary condition tables are given in each major results section.

Component of SEI	Indicator	Condition description	Condition and confidence
BIOASSESSMENT (continued)	Macroinvertebrate and diatom communities – bioassessment models	Roughly 70% and 54% of the streams in the park, based on custom park-scaled macroinvertebrate and diatom models (respectively), were in a reference or pristine reference condition. Pristine reference condition describes the state with no measurable human disturbance – a condition which we consider ecologically meaningful and well connected to the Glacier General Management Plan. A small percentage of streams with potential issues that may be linked to human disturbance were found in the park's front country. The pattern in these results across the park resembled 1) the distribution of human disturbance, 2) several water chemistry measures above their non-reference assessment point concentrations, and 3) select physical habitat metrics that exceeded natural reference levels. This may support a structural relationship between these drivers and ecological response. The Railroad Creek tributary site, the trio of tributaries to the North Fork of the Flathead (Big Creek, Coal Creek, and Canyon Creek), and Divide Creek on the park's east border have historical and ongoing Clean Water Act listings by Montana Department of Environmental Quality for various human caused disturbances in the US Forest Service land to the park's west. We have high confidence in our assessment for these parameters.	
	Macroinvertebrate and diatom communities – Stressor specific bioassessment response to sediment, nutrients, water temperature and metals	We directly link macroinvertebrate and diatom response to important specific stressors in Glacier using existing Montana Department of Environmental Quality models. These assessments may be more diagnostic and potentially useful for resource management in the park. There was some suggestion that macroinvertebrate response to nutrients had a possible connection to human disturbance. Around 30% of the parks streams were above a Montana Department of Environmental Quality threshold for macroinvertebrate response to nutrients. However SEI methods do not quite match the protocol required by the state to implement this assessment point, and given the general lack of non-reference response in other macroinvertebrate metrics, we treat this response with caution. Macroinvertebrate response to sediment likely reflects natural patterns. Montana Department of Environmental Quality models show a small response to sediment, nutrients, and metals in diatom communities and some of these streams were influenced by human disturbance that may have elevated concentrations. We have medium confidence in our assessment for these parameters. Some models may not be well calibrated to the scale of the park and we lack well distributed ecoregional reference sites from which baseline assessment points may be derived. *Of note, our indicator based on macroinvertebrate response to water temperature suggests few of the park's streams were warmer in 2007–2009 than comparable ecoregional reference sites. However, because macroinvertebrate communities tolerant of colder water are strongly associated with higher ecological integrity, ongoing bioassessment will be important as the climate continues to warm.*	
	Aquatic invasive species	Aquatic invasive species can have a strong effect on stream ecological integrity and are a focus of park resource management. We did not detect zebra or quagga mussel, rusty crayfish, or New Zealand mudsnails in our 2007–2009 data (or in any sentinel site data since). Given detections in 2016 of mussels in water samples from reservoirs near the park and confirmed mudsnail populations in northwest Montana, we will closely watch for these and other invasive species in future monitoring. We found the invasive but native diatom, *Didymosphenia geminata* (didymo), in a large portion of the park's streams, often in a bloom state. Research is ongoing on the implications of this to the park's streams and their management. Repeating the parkwide survey will help us better understand patterns in didymo distributions across the park. We have low to medium confidence in our assessment for these parameters. We documented simple presence/absence of five aquatic invasive species (not including fish), and our survey design does not target stream sites with high invasion probabilities. Therefore, this assessment should be used to understand long-term status of aquatic invasive species across the streams of Glacier and not as a planning tool (e.g., for the exclusive identification of potential treatment areas or invasion "hot spots"). *Of note, didymo has complex relationships with nutrients and hydrology. Some research suggests it is connected to patterns driven by climate change and thus warrants careful monitoring.*	

Management applications in Glacier

A fundamental goal of Rocky Mountain Network inventory and long-term monitoring is to provide park managers with data and information useful for protecting and managing park resources. Our estimates of stream ecological integrity can serve as baselines for understanding the current status and future changes or trends in streams in Glacier. This information can help park management report on and meet regulatory requirements and assist with management in the park. Our models can be used to document the condition of individual streams, and that information could be used by park managers to prioritize streams for restoration or enhanced protection. Our data can be used to quantify the importance of various "stressors" or "drivers" of stream condition (e.g., nutrient input, sediment loads, climate change-driven changes in stream hydrology, etc.). Specific indicators, when interpreted in the context of the larger SEI dataset, can also enhance general understanding of stream ecology. Finally, SEI results should also help park staff understand and communicate to the public about the condition of stream resources in Glacier. They allow interpretation of specific streams in the context of the broader resource. They also provide a unique perspective across the park as a whole.

Climate change

Climate change is one of the most pressing issues impacting streams in relatively undisturbed parks like Glacier. The park's remoteness, its large size, and the generally intact current stream condition will probably not insulate important stream resources from broad scale changes in climate. Specifically, climate change will make it more difficult to achieve water chemistry standards in the park, especially in water temperature, hydrology, and sediments (or responses indirectly linked to these). Furthermore many aspects of the biological communities in streams will be directly and indirectly impacted by changes in temperature and precipitation patterns.

Network SEI data as reported here are too short in duration to answer conclusively any questions regarding climate change impacts on the park's streams. We will address temporal patterns in our report on sentinel sites in the park. Yet our broad and representative survey offers a unique perspective and some indication that climate driven effects, especially on stream water temperature, are important. For example, there are interesting patterns across space in our macroinvertebrate bioassessment data, with some models suggesting ecological integrity is higher in systems with colder base flow water temperatures during the late summer. Specific research by partners suggests this might be especially important for temperature sensitive species like the meltwater stonefly.

Perhaps most importantly, network stream monitoring provides a critical ecological baseline for future assessments. This is enhanced by the comprehensive suite of indicators included in the protocol. As just one example, the park's namesake glaciers – such an important part of stream ecology – are projected to be gone soon. This will change stream temperatures, hydrologic regimes, and sediment loads. SEI monitoring may someday document reduced stream flow, channels with less habitat, altered sediments, and warmer water temperatures. All these changes will likely have detrimental impacts to aquatic communities. We hope network data will offer the park useful guidance on how to interpret and manage these systems in the face of these changes.

Future stream monitoring

This effort has been, and will continue to be, a cooperative undertaking between the network and our partners—most importantly, park management. We believe our results, representing the efforts of dedicated scientists and resource managers over several years, are valid, representative, and address our objectives. However, our data are "short" and we are just in the beginning of this effort. It will take many years to have sufficient data to understand long-term trends. As we accrue data we will also continue to improve our understanding of the mechanisms and drivers behind SEI responses. Future SEI monitoring in Glacier will permit continued analysis of SEI data relative to the criteria and thresholds for the state and ecoregions. These analyses will help scientists continue to monitor the most cost-effective and management-relevant suite of indicators of ecological integrity of the streams and rivers of Glacier. Most important, this will eventually allow estimation of trend and a better connection to climate drivers of stream condition.

Acknowledgments

This report was prepared by Rocky Mountain Inventory and Monitoring Network staff based on input and information from many people. Errors are the responsibility of network staff.

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Abbreviations

AIC	Akaike Information Criterion
ATtILA	Analytical Tools Interface for Landscape Assessments
BPJ	best professional judgment
CCE	Crown of the Continent Ecosystem
CDF	cumulative distribution function
CWA	Clean Water Act
EMAP	Environmental Monitoring and Assessment Program
EPA	U.S. Environmental Protection Agency
FLBS	Flathead Lake Biological Station
FSBI	Fine Sediment Biotic Index
Glacier	Glacier National Park
GMP	General Management Plan (National Park Service)
GRSA	Great Sand Dunes National Park and Preserve
GRTS	Generalized Random-Tessellation Strati fied spatially balanced survey design
HBI	Hilsenhoff Biotic Index
HDI	Human Disturbance Index
I&M	Inventory and Monitoring
IPI	Invasive Plant Index
ITIS	Integrated Taxonomic Information System
LDC	least disturbed condition
MDC	minimally disturbed condition
Montana DEQ	Montana Department of Environmental Quality
MMI	Multimetric Index
MMI_{Gd}	diatom multimetric index specific to Glacier National Park
MMI_{Gm}	macroinvertebrate multimetric index specific to Glacier National Park
NAWQA	National Water Quality Assessment
NHD	National Hydrography Database
NLCD	National Land Cover Database
NMDS	nonmetric multidimensional scaling
NPS	National Park Service
ORW	Outstanding Resource Water
OTU	operational taxonomic unit
PCB	polychlorinated biphenyls
PCoA	Principal Coordinates Analysis
QAPP	quality assurance performance plan
QAQC	quality assurance quality control
RBS	relative bed stability
RIVPACS	River Invertebrate Prediction and Classification System
ROS	Regression on Order model
SEI	Stream Ecological Integrity
S:N	signal to noise ratio
SOP	standard operating procedure
TPI	Temperature Preference Index
TSS	total suspended sediment
USFWS	US Fish and Wildlife Service
USGS	US Geological Survey

1 Introduction

1.1 The National Park Service Inventory and Monitoring Program

The purpose of the National Park Service (NPS) Inventory and Monitoring (I&M) Program (Fancy et al. 2009) is to develop and provide scientifically sound information on the current status and long-term trends in the composition, structure, and function of park ecosystems (i.e., ecological integrity). As part of the NPS's effort to improve park management through greater reliance on scientific knowledge, a primary role of the I&M Program is to collect, organize, and make available natural resource data and to contribute to NPS institutional knowledge by facilitating the transformation of data into information through analysis, synthesis, and modeling of specific key vital signs.

The Rocky Mountain Inventory and Monitoring Network (hereafter, network) and its partner parks and scientific collaborators identified 12 high-priority vital signs for focused, long-term monitoring. The vital signs include Wet and Dry Deposition; Weather and Climate; Water Chemistry; Surface Water Dynamics; Freshwater Communities; Invasive/Exotic Aquatic Biota; Groundwater Dynamics; Wetland Communities; Invasive/Exotic Plants; Vegetation Composition, Structure, and Soils; Focal Species (beaver, elk, grizzly bear, and Great Sand Dunes National Park endemic insects); and Landscape Dynamics (Britten et al. 2007).

Stream Ecological Integrity (SEI) monitoring in Glacier National Park (hereafter, Glacier) addresses five of the network's 12 high priority vital signs: Water Chemistry, Surface Water Dynamics, Freshwater Communities, Invasive/Exotic Aquatic Biota, and Invasive/Exotic Plants. Three other high priority vital signs are indirectly linked with the SEI protocol, including: Landscape Dynamics, Wet and Dry Deposition, and Weather and Climate. Network stream monitoring in Glacier is a multifaceted ecological health approach guided by a detailed SEI protocol (Schweiger et al. 2015). The SEI protocol describes an integrated approach to understanding status and trends in stream ecological condition, capturing the strengths of both fixed-site, water chemistry-based approaches and probability surveys. The protocol combines periodic (5–10 years apart) parkwide surveys of streams with annual "sentinel site" monitoring at four select sites.

1.2 Purpose of report

This report presents summaries and general interpretation of SEI monitoring conducted from 2007 to 2009. We focus on data from an extensive survey of 40 randomly selected survey sites and nine hand-picked sites distributed across all of the park's streams and rivers. Because this is the first report on SEI monitoring at Glacier, we include justification and some detail for key elements of the protocol – readers experienced in stream monitoring and assessment may only need to skim the Introduction and Methods sections. We present additional analyses focused on trend in stream condition at four sentinel sites from 2007 to 2015 or 2016 in a companion future report to this document (Schweiger et al. in preparation a).

1.3 Navigating the report for different audiences

This report provides both high-level summaries and comprehensive detail to meet the needs of its two primary audiences: park resource managers and network scientists. We provide high-level results in summary condition tables in the Executive Summary and near the start of each Results section. We include detailed explanation in the main narrative and appendices to document our approach and methodology for those continuing the monitoring work.

1.4 Glacier National Park stream resources

Glacier National Park is located in the "Crown of the Continent" ecosystem in northwest Montana in the northern Rocky Mountains. The Canadian Provinces of Alberta and British Columbia border the park to the north and contain Glacier's sister park, Waterton Lakes National Park (Figure 1). Elevation ranges from 949 to 3,180 m, with the Continental Divide bisecting the park north to south. The park's landscape is characterized by steep, high relief mountains interspersed with glacially carved U-shaped valleys. Glacier contains an extensive network of streams, most of which are high gradient perennial streams (Mast 2007).

Glacier has been called the "water tower of the continent" (Hauer et al. 2016) because it is at the headwaters of three major river systems. Triple Divide Peak in northern Glacier occurs where the Continental and Hudson Divides converge. Waters flowing west enter the Columbia River and eventually the Pacific Ocean; waters flowing northeast enter the Saskatchewan River and the Arctic Ocean; and waters flowing east enter the Missouri River and Gulf of Mexico and ultimately the Atlantic Ocean. The North Fork and Middle Fork of the Flathead River form the western and southern boundary of Glacier. These large rivers are among a very few large rivers in the conterminous 48 US states that are completely unregulated by dams or diversions.

Glacier has some of the cleanest water in the world and is

treasured for its beauty, pristine condition, and ecological integrity (Figure 2; Long 2002). The World Wildlife Fund rates the biological distinctiveness of the Canadian Rockies Ecoregion that contains Glacier as "Continentally Outstanding" (Abell et al. 2000). Much of the Pacific Northwest region was heavily glaciated during the Pleistocene and, therefore, has few known endemic aquatic species. However, the Canadian Rockies Ecoregion served as a refugium for freshwater species during the last glaciation. As a result, Glacier's streams, rivers, and lakes and associated groundwater and wetland systems support a wealth of biodiversity, from plants, including tiny diatoms (unicellular algae), to aquatic insects to amphibians, fish, birds, and mammals. Over 500 taxa of diatoms have been recorded in the park, including several unique and new to science species (Bahls 2009). Aquatic insects are also diverse and include endemic species such as the meltwater stonefly (*Lednia tumana*), which lives in alpine streams immediately downstream of glaciers and snowfields (Muhlfeld et al. 2011).

Glacier waters provide high-quality lentic and lotic fish habitat inhabited by six native salmonids, including the threatened bull trout (*Salvelinus confluentus*) and the state-sensitive west slope cutthroat trout (*Oncorhynchus clarkii lewisi*); both are indicators of high stream ecological integrity. Fourteen other fish species inhabit Glacier waters, including several sculpins (*Cottus* spp.), burbot (*Lota lota*) and northern pike (*Esox lucius*; Downs et al. 2011). The waters of the park also are home to five introduced nonnative salmonids, which affect and are of great concern to park management. Other aquatic or partially aquatic species of note include the Rocky Mountain tailed frog (*Ascaphus montanus)*, common loon (*Gavia immer*), harlequin duck (*Histrionicus histrionicus*), American dipper (*Cinclus mexicanus*), northern water shrew (*Sorex palustris*), beaver (*Castor canadensis*), and the river otter (*Lutra canadensis*). Nearly every terrestrial species in the park interacts with streams and rivers at some point in its life cycle.

1.5 Why monitor streams in Glacier National Park?

There are several reasons behind the choice to conduct long-term stream monitoring in Glacier. In general, streams are fundamental components of the ecological and cultural context of Glacier (Stottlemyer et al. 1997; Hauer et al. 2000; Seastedt et al. 2004; Mast et al. 2005; Hauer et al. 2007). They are often what visitors come to see, what visitors remember when they leave, and they have played an important role in the history (Figure 3) and mythology of the park. Perhaps most importantly, the NPS recognizes that aquatic resources are some of the most critical and biologically important resources in the national park system and that they are vulnerable to degradation from activities both within and external to parks.

1.5.1 Ecological integrity

Understanding and managing the streams and rivers of Glacier is best accomplished by treating them as complete hydrologic systems within a watershed where the natural processes that deliver water, sediment, and woody debris are maintained and human disturbances are minimized. Network monitoring aims to provide data and understanding of the hydrologic systems within network parks and the natural processes that streams and rivers support. While the regulatory considerations summarized below also provide an important context for SEI monitoring, the emphasis on long-term ecological monitoring within the protocol is a key distinction from other monitoring conducted by states or other federal agencies like the Environmental Protection Agency (EPA).

SEI monitoring focuses on the estimation and the interpretation of the ecological integrity of streams and rivers in the park (Schweiger et al. 2015). Ecological integrity is the capacity to support and maintain a balanced, integrated, and adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of natural habitats of the region (Karr 1991). It is a complex, multidimensional concept and usually a single indicator is insufficient to characterize it. Therefore, we use an integrated set of response measures, including community-level benthic macroinvertebrate and algae (primarily diatoms) structure and composition, detailed physical habitat, including stream hydrology, and water chemistry. Our primary focus is on multimetric and multivariate indices of stream ecological integrity from macroinvertebrate and diatom data (Schweiger et al. 2015). We use indicators of human disturbance or stress to help understand patterns in these responses and develop bioassessment models of stream condition.

Climate change has impacted and will likely continue to significantly impact Glacier's aquatic resources (Hauer et al. 1997; Giersch et al. 2016; McKernan et al. 2018). In general it will likely make it more difficult to achieve water chemistry standards in the park (Field et al. 2007). While there is regional variation, projected effects across the West include loss of glaciers, less snow, earlier peak flows, less stream flow, warmer water temperatures, more frequent droughts, and more intense storms. The interacting effects of climate

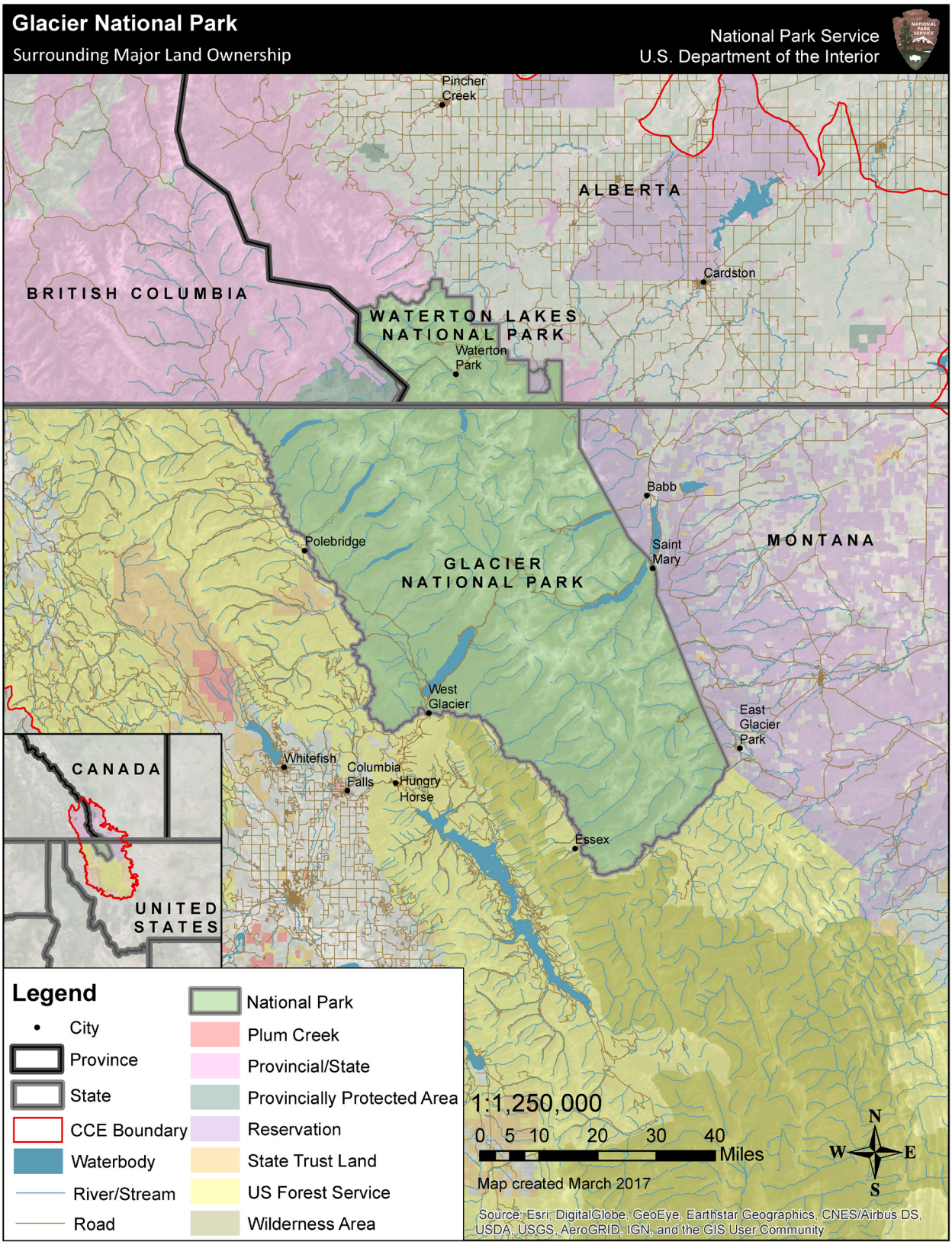


Figure 1. Major land ownership and other key features in and around Glacier National Park, Montana, USA, and Waterton Lakes National Park, Alberta, Canada. Inset shows location of the parks in the western United States and Canada and includes the boundary of the Crown of the Continent (CCE) region.

Figure 2. Haystack Creek in Glacier National Park. (NPS)



change with other stressors, such as pollution, ultraviolet light, diseases, and environmental toxins, are complex. Moreover, the ramification of changes in food-web structure and dynamics caused by the loss of some species and the expansion of others is unclear. Nevertheless, climate-induced changes in the hydrologic cycle and multiple proximate direct disturbances often lead to changes in species distribution, including invasion by taxa that can threaten native or endemic species and the stability of aquatic ecosystems (Rahel and Olden 2008). The network considers the possible impacts of climate change on ecological integrity in the park's streams as one of the primary reasons why a comprehensive approach to long-term monitoring of streams is required, as this may be the best way to sort out any uncertainties associated with climate change.

1.5.2 Regulatory considerations

Regulatory considerations under the NPS Organic Act, the Clean Water Act (CWA), and other laws, regulations, and policies relative to network stream monitoring are summarized in the network SEI protocol (Schweiger et al. 2015). While regulatory considerations provide important context, they do not drive the design of SEI monitoring. The park is the lead on any regulatory matter.

1.6 Monitoring objectives

The general goals for long-term ecological monitoring of Glacier streams focus on documenting the status and trend in extent and condition, helping to understand the causes of changes, especially where change is relatable to human disturbance, and assisting in the application of SEI results and relevant auxiliary information to park management. While not an objective per se, SEI monitoring in Glacier does serve to add to the general ecological knowledge regarding streams and rivers in the park. The following two sections summarize our objectives (see Schweiger et al. (2015) for more detail).

1.6.1 Population scale status

This report includes data from only our first Glacier stream survey and lacks repeat data. We can therefore only estimate population scale status. Trend at the population scale will be estimated in future reports.

1. Determine the status in stream length, using
    A. Remotely sensed data
    B. 2007–2009 survey extent data
2. Determine status in a suite of response measures:
    A. Human disturbance

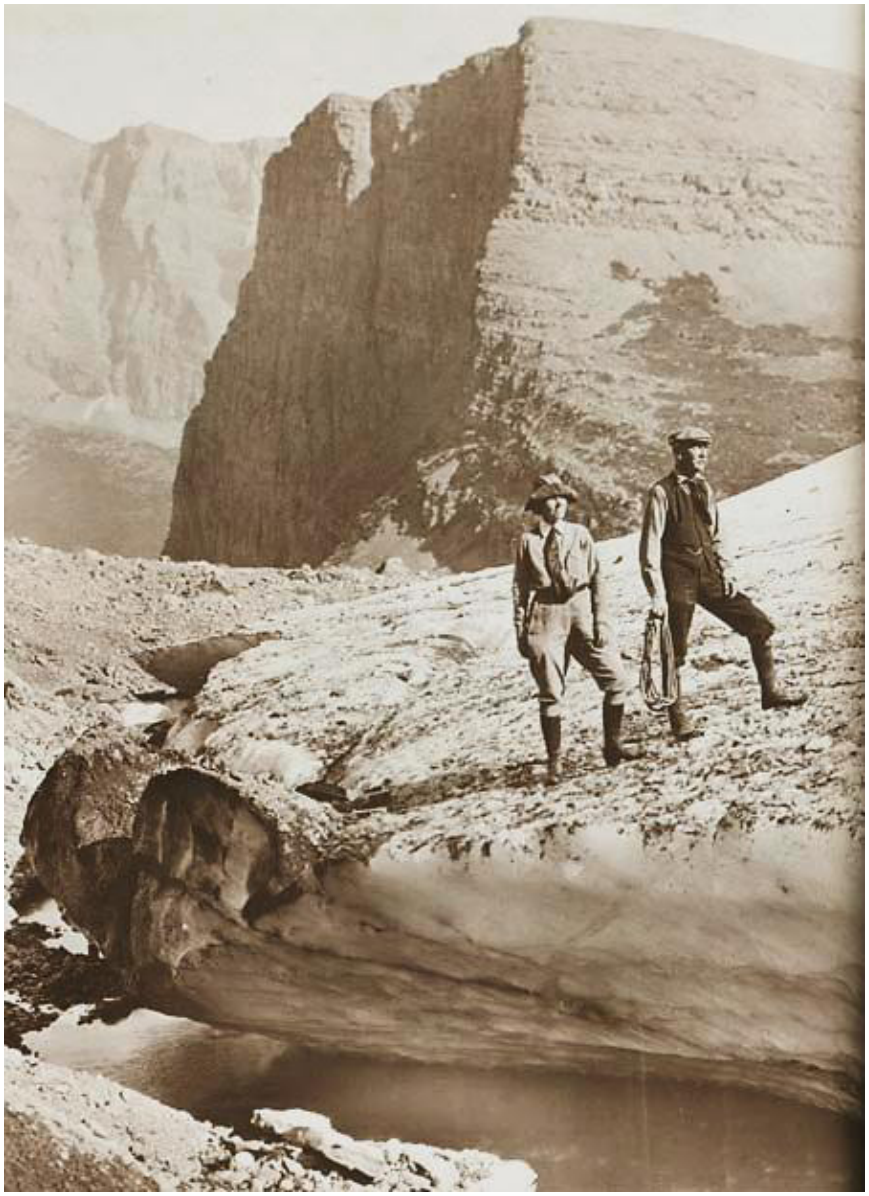


Figure 3. Early park visitors on Grinnell Glacier just above its stream meltwater zone. Photo courtesy of the Glacier Natural History Association (Buchholtz 1976).

B. Water chemistry

C. Physical habitat

D. Macroinvertebrate and diatom community composition as indicators of ecological integrity

3. Assess status of select responses detailed in objective 2a–d through comparisons with the following assessment points:

A. Glacier management derived assessment points (which may include any of the following b–d assessment points)

B. Relevant state/federal/tribal nation regulatory criteria

C. Ecological thresholds

D. Ecoregion assessment points derived from reference site data within and around Glacier using SEI survey data (preferable) or partner/auxiliary data

1.6.2 Site specific status

We estimate site specific status for all sampled sites (or a subset based on stream type or location), including specific sentinel sites. Analyses of these data do not use design-based methods and are specific to the sites only. Statistically rigorous estimates of trend at sentinel sites are possible after five to ten years of monitoring and are presented in Schweiger et al. (in preparation a).

4. Determine the status for select sites in a suite of response measures (as in objective 2a–d)

5. Assess the status of select responses at specific sites, as in objective 4
6. Relate spatial patterns in select stream responses detailed in objectives 2a–d to important ecological and anthropogenic drivers; models depend on scale appropriate covariate SEI and auxiliary data (e.g., stream temperature and precipitation) with clear connections to SEI responses

2 Methods

The following sections present brief summaries of how and why sites were selected, how data were collected in the field or harvested from auxiliary sources, and how data were analyzed and interpreted. For a more complete treatment see the network SEI monitoring protocol (Schweiger et al. 2015) and the appendices to this report.

2.1 Sample designs and stream monitoring sites

Sample designs define locations in space for the collection of data, sample sizes required to meet monitoring objectives, and the strategy for arraying samples across time (Olsen et al. 1999). We employed a suite of three sample designs (Table 1): (1) "random" probabilistic surveys, (2) targeted hand-picked sentinel designs, and (3) targeted model-based gradient designs. Figure A1 presents site name and number for all sites together.

2.1.1 Survey

A distinguishing feature of the SEI protocol in Glacier is a survey design approach to locating most stream monitoring locations. This random selection allows valid statistical inference to the population of streams in the park, with known confidence, from a relatively small sample. Figure 4 and Appendix A present survey sites in Glacier as sampled in the 2007–2009 survey and analyzed as part of the survey design.

We used a generalized random-tessellation stratified (GRTS) spatially balanced algorithm to select primary sample locations and an oversample of potential sample locations (Stevens and Olsen 2004; Figure 4). Our target population included all sampleable, perennial at the time of the sample, non-artificial (i.e., no canals or ditches), flowing (i.e., no lakes or wetland) water within the park. "Sampleable" is defined based on accessibility and administrative access. We used a modified high resolution (1:24k) stream hydrography database from the USGS National Hydrography Database (NHD; USGS 2017b) clipped to the park boundary as our sample frame. We incorporated accessibility into the design via a cost surface. Cost surfaces are derived from a GIS model (Theobald et al. 2010) that generates a grid of the estimated time required to access any point in the park. We developed a revisit design (how sites are sampled through time) based on a balance between operational constraints across all network protocols and the power of the design to detect trend and provide precise status estimates (Schweiger et al. 2015).

2.1.2 Sentinel

Glacier sentinel monitoring uses a different design and analysis approach than the survey to allocate sites across space and events across time. The most important distinguishing features are (1) an expert opinion or judgment-based selection of stream site locations, (2) multiple samples at each site per year, and (3) no intention to make inference beyond the site or immediate stream reach without complex modeling or explicit assumptions.

Sentinel sites were located subjectively based on a suite of criteria developed by network staff, collaborators (especially scientists who have been working in Glacier streams for decades), and Glacier staff. Most importantly, sentinel sites were located based on an expectation that the sites are important and useful for understanding site specific patterns in stream condition over time.

Sentinel sites in Glacier include the North Fork of the Flathead at the park border, Ole Creek in the southwestern corner of the park, Reynolds Creek at the top of Logan Pass, and Swiftcurrent Creek on the east side of the park (Figure 5). The North Fork and Swiftcurrent sites were selected because of the long-term data that are already being collected by USGS, and because they each represent important stream and watershed types in the park. The Reynolds site was selected because it is one of the few accessible alpine streams in the park. Ole Creek was selected because it is a monitoring site for the Montana Department of Fish, Wildlife and Parks and is representative of an important stream type in the park.

Table 1. Summary of sample designs used in Glacier National Park Stream Ecological Integrity monitoring. GRTS = generalized random-tessellation stratified spatially balanced design. Event counts are for complete sample events (additional partial visits not included here) and are through 2013, except where noted.

Survey sites	Sentinel sites	Gradient sites
All perennial, non-artificial and flowing water within the park, with a total target sample size of 40, mostly sampled once every 5–10 years (a subset of the sites are revisited within each survey implementation). Design is a GRTS with unequal probability sampling across accessibility weighted stream order classes. In the 2007–2009 survey, we conducted 75 full events at survey sites.	Four sentinel sites, sampled annually four times per season. As of 2015, there were 37 full events at these sites, with an additional 88 partial events.	Six sites sampled once or twice each every 5–10 years. As of 2015, these sites had been sampled seven times.

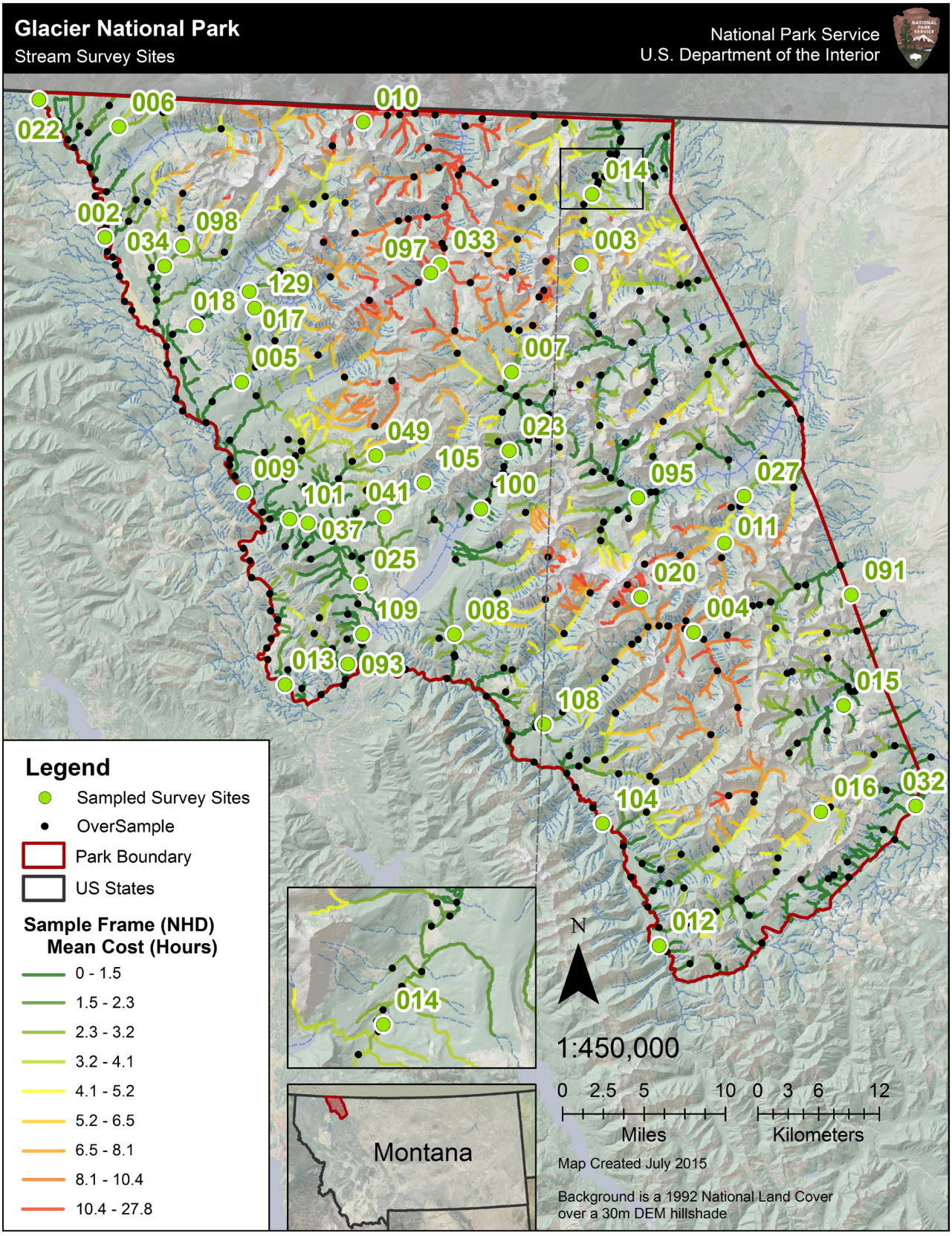


Figure 4. Stream survey sites in Glacier National Park, sampled in 2007–2009. The stream network (from the National Hydrography Dataset (NHD; USGS 2017b)) used as the sample frame is color coded by accessibility, with redder colors indicating longer access times. Insets show detail of the sample frame and the location of the park in Montana. For corresponding site names, see Appendix A.

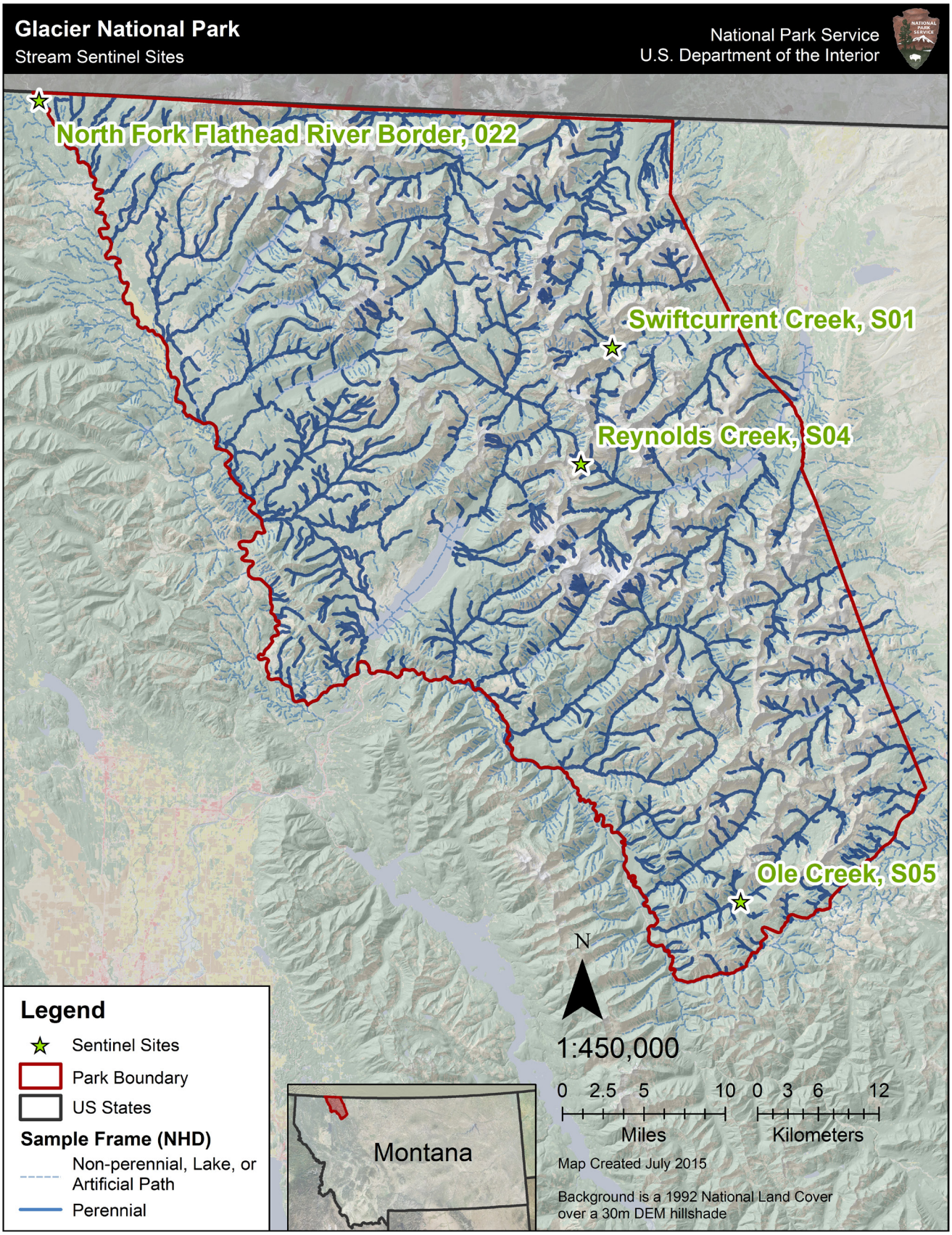


Figure 5. Stream sentinel sites in Glacier National Park sampled in 2007–2009. The inset shows the location of the park in Montana. NHD is the US Geological Survey National Hydrography Database.

2.1.3 Gradient

The Glacier gradient design is similar to the sentinel design in several aspects, including (1) an expert opinion or judgment-based selection of stream sites, and (2) no intention to make inference beyond the sites or the sentinel stream complex. However, the criteria used to locate gradient sites differ from those used to identify sentinel sites. Data from gradient sites are primarily used to characterize stream condition at the extremes of anthropogenic and natural disturbance conditions that influence stream ecology. Therefore, sites are targeted to streams we expect to be under stress or in pristine condition relative to the complete population of streams in the park. Figure 6 shows the 14 gradient sites across the park.

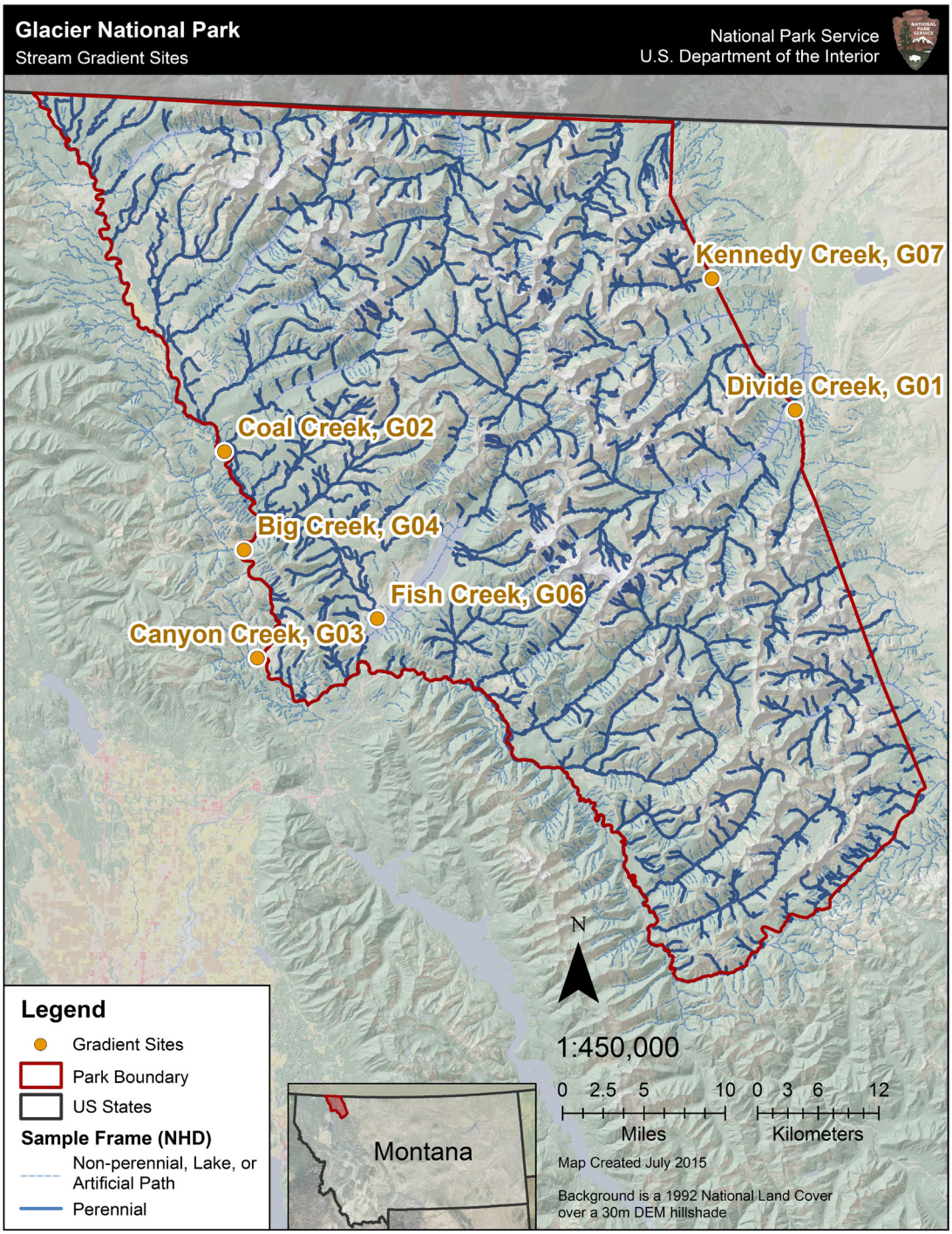


Figure 6. Stream gradient sites in Glacier National Park sampled in 2007–2009. Inset shows the location of the park in Montana. NHD is the US Geological Survey National Hydrography Database.

2.2 Field and lab methods

All field methods are described in Schweiger, O'Gan, et al. (2016) and only briefly summarized here. All laboratory methods follow standard and accepted protocols implemented by each individual lab and include detailed quality assurance and control methods. This includes how cooperator labs specify their ability to detect very low concentrations of a chemical parameter. The network requires labs to define at least a method detection limit(s) (MDL) as the minimum measured concentration of a substance that can be reported with 99% confidence that the measured concentration is distinguishable from method blank results (EPA 2016a). The SEI protocol includes an overarching draft Quality Assurance Project Plan (QAPP) that summarizes laboratory methods and quality assurance and control aspects within SEI monitoring. Appendix B provides an overview and reports MDL by lab, year, and parameter.

Stream monitoring field methods are relatively well established and we draw upon this wealth of knowledge for the network SEI protocol. Sources of SEI methods include the EPA Environmental Monitoring and Assessment Program (EMAP; Stoddard et al. 2005), Flathead Lake Biological Station (FLBS; R. Hauer, pers. comm. 2007), U.S. Forest Service (Heitke et al. 2011), NPS Water Resources Division (WRD; Irwin 2006), USGS long term water quality monitoring (e.g., Fitzpatrick et al. 1998), and the Montana Department of Environmental Quality (Montana DEQ) (Montana DEQ 2012a).

2.2.1 Indicators

The SEI protocol includes a broad spectrum of indicators to help evaluate the ecological integrity of streams in Glacier (Table 2). We include measures of both drivers and ecological responses, such that we may better understand the linkages between these and help the park apply network monitoring data to resource management. Core indicators include multiple measures of water and sediment quality (i.e., nutrients, metals, temperature); physical habitat (i.e., substrate composition, riparian cover, channel geomorphology, instantaneous stream discharge); and community level assays of two important biological assemblages, macroinvertebrates and algae (including both soft bodied algae and diatoms, collectively referred to as perpihyton). The biological assemblages provide an integrated aspect for assessing ecological integrity because these organisms respond to environmental conditions over time and space. In addition, as part of the assessment of physical habitat, crews assess 12 types of potential physical human disturbances ("human influence" in Table 2) at each site and approximate their intensities based on proximity to the stream channel. These data are collected at each of the 22 riparian plots along the sample reach. They are summarized into a Human Disturbance Index (HDI, see below). Many of the models we develop relate the gradient in HDI to synthetic bioassessment and other physical habitat metrics.

2.2.2 Sample reach

The design of the sample reach follows the EPA's EMAP site layout (Peck et al. 2006) as modified by the network SEI protocol (Figure 7; Schweiger et al. 2015). For wadeable sites, a reach measuring 40 times the mean wetted width is established. Eleven cross-section transects, used for physical habitat characterization and biological subsampling, are placed at equal intervals along the reach. Point samples for sediment, macroinvertebrate, and algae collection are set up at middle, left, or right locations on each of these transects. Riparian plots measuring 10 × 10 m are established on the banks at each transect for collecting riparian vegetation attributes. A thalweg profile is established in the deepest part of the channel along the entire sample reach. Water and sediment chemistry is collected at the downstream end of the sample reach. At non-wadeable sites, the reach is extended up to 2500 meters, with select modifications in layout to accommodate sampling from a raft. These sample reach lengths capture repeating patterns of local habitat structure and biological variability associated with riffle-pool structure and meander-bend morphology (see Kaufmann et al. 1999 and references within). These site layouts (or similar derivatives) are used by several other long-term monitoring programs.

2.3 Auxiliary data

We use several datasets not generated within the SEI protocol in order to enhance our ability to characterize and interpret the condition of the streams of the park. These data come from monitoring efforts conducted by state and other federal agencies or national scale remotely sensed data collection efforts. Table 3 lists auxiliary data, sources, and the metrics or variables created from them as used in this report. Figure 8 maps reference and other sites where site level chemistry, habitat, and biological auxiliary data were harvested from. We map the location of all (reference and otherwise) auxiliary sites in Figure 8 but only use data from the reference sites (sites with minor or negligible disturbance) in our ecoregional assessment points. We present a summary of these metrics in further detail in Appendix C, as some are specific to analyses of Glacier data and not defined in detail in the SEI protocol. Note that dozens of other variables were created from these and similar data sources but were not used in our current analyses.

Table 2. Summary of field data collected within the Stream Ecological Integrity protocol at Glacier National Park.

Type	Water source
Water chemistry	In Situ temperature (synoptic and continuous), water; oxygen, dissolved; pH; specific conductance
	Major ions alkalinity, dissolved; calcium, dissolved; chloride, dissolved; fluoride, dissolved; hardness, dissolved; magnesium, dissolved; potassium, dissolved; silica, dissolved; sodium, dissolved; sulfate, dissolved; total suspended sediments
	Nutrients ammonia, dissolved; nitrite + nitrate, dissolved; nitrite, dissolved; nitrate, dissolved; nitrogen, total; orthophosphate, dissolved; phosphorous, total; carbon, organic, dissolved; carbon, organic, total; chlorophyll-a in periphyton; ash free dry mass in periphyton
	Metals in water aluminum, arsenic, barium, beryllium, cadmium, chromium, copper, iron, lead, manganese, selenium, zinc
	Metals in sediment aluminum, total; arsenic, total; barium, total; beryllium, total; cadmium, total; chromium, total; copper, total; lead, total; iron, total; mercury, total; selenium, total; silver, total; zinc, total
Physical habitat	Instantaneous discharge
	Continuous discharge (from nearby USGS gauge if available
	Thalweg profile
	Channel geomorphology
	Woody debris tally
	Channel dimensions
	Substrate quantification
	Fish cover
	Riparian vegetation
	Human influence
	Assessment of channel constraint, debris torrents, and major floods
Macroinvertebrates	Reach-wide (composited across systematic transects) sample
	Operational Taxonomic Unit level identification for a target count of 600 individual specimens in a sample
Algae	Reach-wide (composited across systematic transects) sample
	~Species level identification for a target count of 600 individual specimens in a sample

2.4 Analyses

By design, SEI monitoring is information rich. Distilling this large amount of information into meaningful reports is a challenge; however, the diversity and extent of SEI results provide many opportunities for enhanced interpretation of status and trend of stream condition at Glacier. Schweiger et al. (2015) provides a summary of the general SEI analytical approach and Appendix D provides specific details. The network analytical strategy also incorporates feedback from park management and protocol review for purposes of improving efficiency (e.g., modifying sample sizes or response measure selection to lower costs or enhance precision). A summary of important analytical detail follows.

2.4.1 Synthetic metrics

We address several objectives by estimating derived indices from SEI monitoring data. These include synthetic metrics for human disturbance, macroinvertebrate and diatom community structure as indicators of ecological integrity, and select physical habitat attributes. The creation of these indices involves complex analyses that are in and of themselves informative. Many of these indices are also used in estimates of status and/or included as important covariates in models.

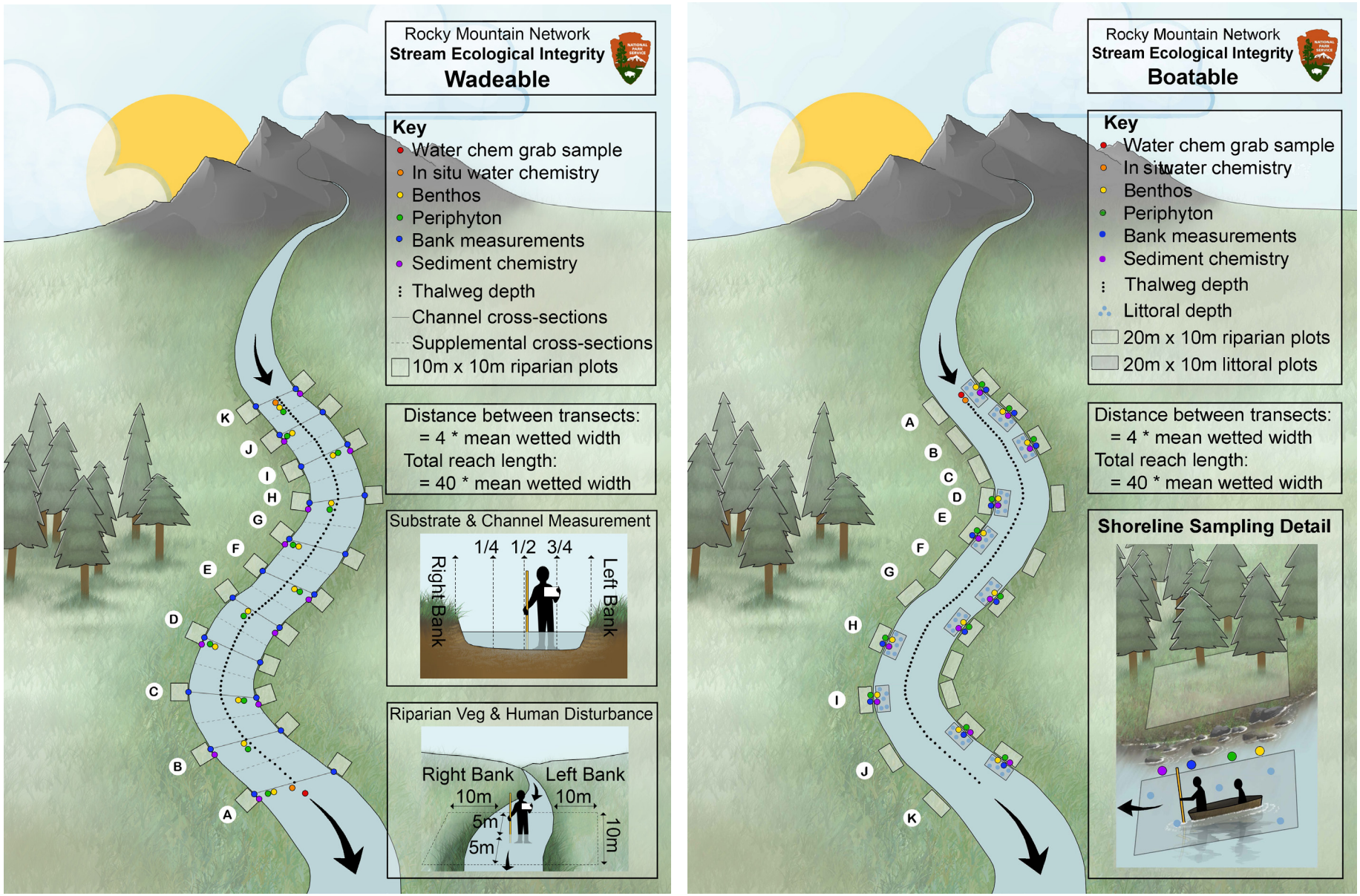


Figure 7. Stream Ecological Integrity sample stream reach plot in oblique profile: (a) wadeable, (b) boatable. Stream flow is from the top to bottom of the figure. Sub-sample locations, riparian plots, and the thalweg profile are all shown. Inset pictures show details for sampling.

Table 3. Summary of auxiliary data sources and metrics used in models of Glacier National Park Stream Ecological Integrity.

Category	Parameter	Units	Source
Climate	Precipitation (annual, 30 year normal)	cm	PRISM Climate Group (2017)
	Ambient air temperature in catchment (annual, 30 year normal)	°C	PRISM Climate Group (2017)
	Stream water temperature in catchment (min, max, mean: August)	°C	Isaak et al. (2016)
Geophysical	Stream slope	degrees	USGS (2017a)
	Percent of catchment as glacier	%	USGS (2017b), GLAC GIS
	Percent of watershed burned over last 5 and last 25 years	%	GLAC GIS*
	Distance to upstream lake outlet	km	USGS (2017b), GLAC GIS
	Watershed membership	categorical	GLAC GIS*
	Continental divide position	categorical	GLAC GIS*
	Elevation	m	USGS (2017a)
	Stream order (Strahler)	Index	USGS (2017b); Strahler (1952)
	Catchment size	m^2	USGS (2017a), GLAC GIS*
	Runoff	mm	Wolock and McCabe (1999)
Disturbance	Road density	length per unit area in catchment	US Census Bureau (2017), GLAC GIS*
	Road–stream crossing	number per unit area in catchment	US Census Bureau (2017), GLAC GIS*, Riitters et al. (2000)
	Distance to nearest road	km	US Census Bureau (2017), GLAC GIS*
	Landcover/use	%	USGS (2017c); Hop et al. (2007)
	Structures	count	GLAC GIS*
Biological	Macroinvertebrate bioassessment metrics (see bioassessment results)	index	Stoddard et al. (2005); EPA (2016b); Montana DEQ (2009)
	Diatom bioassessment metrics (see bioassessment results)	Index	Stoddard et al. (2005); EPA (2016b); Montana DEQ (2009)
Physical habitat	Habitat metrics (see physical habitat results)	index	Stoddard et al. (2005); EPA (2016b); Montana DEQ (2009)
Water chemistry	Nutrients, *in situ*, major ions (see water chemistry results)	mg/l	Stoddard et al. (2005); EPA (2016b); Montana DEQ (2009)

*GIS = Geographic Information System; GLAC = Glacier National Park

2.4.1.1 Human disturbance

Data estimating aspects of human disturbance are synthesized into a composite Human Disturbance Index (HDI). (See list of component metrics and promixity classes for HDI on p. 16). The HDI provides an independent gradient against which measures of stream condition and other SEI responses, such as physical habitat metrics, are assessed to determine how changes in disturbance regimes across the park or over time affect stream condition response.

The component metrics in the HDI are modified from EPA (Stoddard et al. 2006, 2008) and other stream condition assessment methods (Montana DEQ 2005). They are mostly categorical measures that score the presence of various human disturbance categories and rank their likely influence based on their spatial proximity to the stream channel. Note that several metrics are also evaluated or confirmed in the office using a GIS, as in some cases GIS data will be more precise and accurate. The HDI is estimated by first calculating the number of riparian stations at which a particular type of disturbance was observed, weighting each observation according to its proximity to the stream, and then averaging over the riparian stations on the reach. Weightings are as in the list of proximity classes on p. 16. This weighted average is then normalized such that site(s) with the highest score (greatest human disturbance) were equal to 1.0. Sites where crews observed a complete lack of any human disturbance in or near the site were scored as a 0. This index is equivalent to the "W1_HALL" index used by the US EMAP program (Kaufmann et al. 1999) and with modifications by Montana DEQ (Suplee et al. 2005).

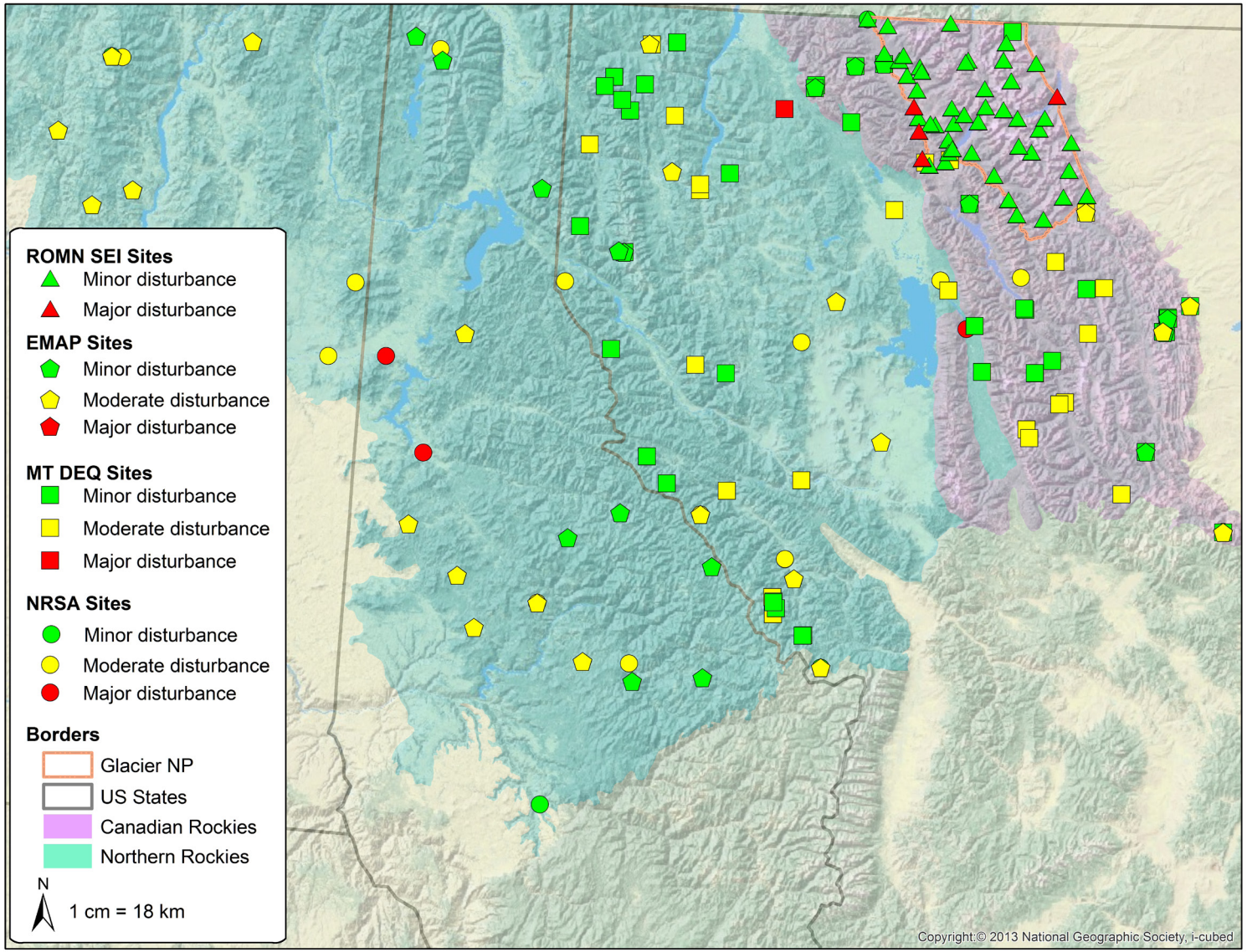


Figure 8. Auxiliary data monitoring sites in the Northern and Canadian Rockies Ecoregions used in comparison with select Rocky Mountain Network (ROMN) Stream Ecological Integrity (SEI) monitoring sites in Glacier National Park for stream water chemistry, physical habitat, and biological variables. MT DEQ = Montana Department of Environmental Quality, EMAP = EPA Environmental Monitoring and Assessment Program, NRSA = EPA National Rivers and Streams Assessment. Most sites were sampled between 2001 and 2009. Some sites were sampled by more than one program. Sites are classified into major/moderate/minor disturbance classes by the program that established the sites (note we use Montana DEQ methods for Glacier Stream Ecological Integrity (SEI) a priori disturbance classifications). Not all sites have all auxiliary data used in this report.

Component metrics of the Human Disturbance Index (categories of human disturbance):

- Walls, dikes, revetments, riprap, or dams
- Buildings or other built structures
- Cleared lots
- (e.g., paved, graveled/dirt parking lot, foundations)
- Roads (paved or not) or railroads
- Inlet or outlet pipes
- Landfills or trash
- (e.g., cans, bottles, trash heaps)
- Parks or maintained lawns
- Row crops
- Pastures, rangeland, hay fields, or other evidence of livestock
- Logging
- Mining (including gravel mining);
- Park trails/campgrounds or other low-intensity facilities.
- Density of road–stream crossings in site's watershed (Riitters et al. 2000)

Proximity classes of the Human Disturbance Index (proximity classes are not applied to estimates of stream road crossing):

- Bank - Present within stream or on the stream bank (weight 1.5)
- Close - Present within the 10 x 10 m riparian plot area, but away from the riparian plot (weight 1.0)
- Present - Present, but outside the riparian plot area (weight 0.667)
- Absent

In our preliminary analyses of the W1_HALL metric as applied to the Glacier SEI 2007–2009 dataset, we observed that in some cases likely human disturbances spread across a broader scale were not included – crews often had no knowledge of human disturbance far removed from the site. We therefore evaluated several additional metrics to include in the HDI that might capture this. Given that road effects on aquatic systems have been especially well documented (Forman and Alexander 1998; Spellerberg 1998; Trombulak and Frissell 2000; McBride and Booth 2005), even if the roads in question are remote and not adjacent to a stream (Theobald 2005), we developed a metric estimating the density of road–stream crossings per unit area in each site's catchment (Riitters et al. 2000). This metric is correlated with a simpler estimate of road density, but by focusing on actual crossings, it better isolates impacts resulting from interactions between roads and streams at a crossing (Figure 9). We normalize this metric such that the site with the highest density of road–stream crossings is equal to 1.0 and sites with no roads intersecting streams in their catchment are equal to 0. The final HDI is then the simple average of the normalized W1_HALL and the normalized road–stream crossing density metric.



Figure 9. Ric Hauer from the Flathead Lake Biological Station samples the North Fork of the Flathead near a road–stream crossing north of Glacier National Park in British Columbia, Canada, 2008. (NPS/BILLY SCHWEIGER).

2.4.1.2 Bioassessment

The primary way in which we analyze and interpret biological data is through bioassessment (Barbour et al. 2000). Bioassessment is, generally speaking, the use of biologically based response measures to assess and monitor natural systems. We use the approach to further meet objectives two

and four (determine the status for the population of streams in Glacier or select sites) as a synthetic way to estimate stream status (Schweiger et al. 2015). Bioassessment assumes that the composition of biological communities reflects the overall ecological integrity of a system. Evidence suggests it may detect stressors that other approaches fail to reveal and that it is an efficient, integrative way of conducting long-term monitoring (Karr and Dudley 1981; Karr and Chu 1997). Bioassessment has become a central element of most federal, state, and other monitoring programs.

We employ bioassessment in three ways. First, we develop Glacier-specific models for macroinvertebrates and diatoms that respond to the suite of anthropogenic and natural stressors or drivers in Glacier. Schoolmaster, Grace, and Schweiger (2012), Schoolmaster, Grace, et al. (2012), and Schoolmaster et al. (2013) refine the theory behind Multimetric Indices (MMIs) and present the methods we use in detail. Overall, this modeling approach requires fewer assumptions and is more efficient with the given information than classic MMI methods (for example as used by Montana DEQ); thus, it represents an important advance for creating synthetic bioassessments of system response. Appendix D provides details on these methods and how we develop custom MMIs for Glacier streams.

Second, we implement existing models developed by Montana DEQ for macroinvertebrates and diatoms. These models are generally more robust at ecoregional or state scales. They are the primary bioassessment tools used by Montana DEQ (and the EPA) and thus are the default tools used by these partners when they evaluate stream condition in and around Glacier. We include metrics from a model called River Invertebrate Prediction and Classification (RIVPACS; Montana DEQ 2012a).

Third, we use stressor specific models that directly link macroinvertebrate or diatom response to important specific stressors (i.e., fine sediments, nutrients) in Glacier. Stressor specific metrics may provide more actionable guidance to park resource management, linking ecological response to a specific stressor. Diagnostic indices such as these are an important component of applied bioassessment (Clews and Omerod 2008; Friberg 2010), especially in the NPS.

2.4.1.3 Physical habitat metrics

Kaufmann et al. (1999) define physical habitat as structural attributes of streams that influence or provide sustenance to organisms within a stream. By definition we exclude physical aspects of water quality, such as water clarity, temperature, and light intensity. It does include biological aspects, such as riparian vegetation and large woody debris in and near the channel, because of their role in modifying habitat structure. Many aspects of stream habitat can be both a response to external disturbances and a measure of stress on the ecological condition of streams. However, when not in a reference or long-term baseline state, we treat indicators of physical habitat as potential stressors on stream ecological condition. This is most obvious with our estimates of human disturbance, including the derived HDI summarized above.

The large number of raw physical habitat measures collected during a SEI sample event are summarized over all subsamples (see Figure 7) into multiple metrics of physical habitat because the SEI protocol uses the sample reach scale. Many physical habitat metrics are synthetic, integrating diverse facets across space and time (e.g., Kaufmann et al. 2008). Using guidance in Kaufmann et al. (1999), Stoddard et al. (2005) and US Fish and Wildlife Service (USFWS 1998), we focus on 33 metrics in this report (selected from over 100 available metrics). These include summaries of areal cover estimates, more detailed and specific approaches for estimating woody debris, residual pool characteristics, sinuosity, and bed stability. Schweiger et al. (2015) and Appendix D provide additional details.

2.4.2 Modeling non-detections

All analyses presented here were done using data adjusted for non-detects via Regression of Order (ROS) imputation models (Hirsch et al. 1991). ROS is a form of imputation that fits a log-normal distribution to observations to estimate the distribution of values below detection limit(s). This is an appropriate method for 2007–2009 data if we assume there were no seasonal effects in these three years of base flow index period samples. All ROS models with sufficient sample size were significant and produced estimated values for non-detects (more appropriate data for summarization). For completeness we also include responses that had non-significant ROS models even though there are no actual results to report, as this could change with better ROS models in the future.

2.4.3 Status

All analyses presented here address objectives focused on estimating and understanding the status in a response – see Appendix D for a more detailed summary. We define status as a "snap shot" evaluation of an SEI response over a well-defined and relatively concise range in time (Olsen et al. 1999). It is estimated using a variety of tools for all SEI variables. Trend is estimated for Glacier SEI sentinel sites in Schweiger et al. (in preparation a).

2.4.3.1 Objectives 1 and 2

For objectives one and two (determine population scale status in stream length and a suite of response measures), we use data from survey sites and design-based analyses that provide inference to an extensive target population of the park's streams. Design-based analyses are well specified (Horvitz and Thompson 1952; Overton and Stehman 1996; Stevens 1997) and are the foundation of long-established analyses used in socioeconomics, politics, medicine, and other fields. While beyond our scope here, in summary, design-based analyses use the inclusion probabilities (or sampling weights) from the design to extrapolate results or provide inference to unsampled elements of the target population. Results from design-based analyses apply (with the precision given in a confidence interval or standard error about an estimate) to all sampleable streams in Glacier in 2007–2009. We report design-based results for SEI responses in tables and for select examples in plots (using a cumulative distribution function; CDF). CDFs include a confidence interval around the distribution of probabilities as estimates of the uncertainty in population scale inference (Stevens 1997).

2.4.3.2 Objective 3

For the assessment of population scale results (objective three) where assessment points are known, we estimate and graphically show the proportion and/or real unit-based extent of a stream response that is above or below the assessment point and interpret these patterns using ecological theory and NPS management guidance. This process is well suited to figures created from CDFs as we can locate the proportion and/or real unit-based percentage of the response that is above or below the assessment point on these plots. We also use simple pie charts to illustrate the proportion of a population in an assessment class – although these limit the inclusion of estimates of the variance around a value and should be used with caution

2.4.3.3 Objectives 4 and 5

For objective four (determine status at a site scale), we use a variety of traditional model-based analyses. Importantly, model-based results, including both simple descriptive statistics as well as more complex predictive models, apply only to the sites included in an analysis. In general we summarize data as means (or medians) and always include various measures of the variance around these statistics. Results are presented in simple tables and with a variety of graphics. For the assessment of site scale results (objective five), we follow the methods given below in the assessment and interpretation section.

2.4.3.4 Objective 6

Objective six (relate spatial and temporal patterns in select stream responses to important ecological and anthropogenic drivers) requires more complex analyses that facilitate understanding ecological and statistical connections among SEI responses, drivers of stream condition, and important covariates that influence these patterns. To address this we develop exploratory linear models of select responses, focusing on independent variables (also referred to as drivers or predictors) that might best help understand patterns in a response and that therefore might aid in stream management. Importantly, these models apply only to the sampled sites and we make no inference to unsampled streams in Glacier. However, given our representative sample design, we expect the results to be broadly generalizable.

2.4.3.5 Model development and assumptions

We keep these models as simple as possible by assuming all independent variables are fixed effects and we omit interaction terms. Given limitations in sample size and period of record, we do not consider these models to be predictive or tests of any hypothesis. Rather they are (examples of) explorations into potentially important connections amongst key estimates of a stream response. While these models are in essence descriptive and limited in predicting novel data, they are useful in that they reveal patterns and connections that might assist the park in improving or protecting stream condition. Future work may support complementary predictive models, with more rigorous confirmation via techniques such as cross validation.

We tested each candidate variable for the assumptions of linear models and transformed as needed. We selected candidate independent variables for each model using a series of steps. First, we developed an initial list based on inclusion of interpretable variables from across the classes of responses measured in SEI monitoring. Second we used variables that were not confounded with one another based on checks for multicollinearity, choosing the most interpretable variable from pairs or sets of highly correlated variables. We then conducted forwards and backwards stepwise selection based on Akaike Information Criterion (AIC) values (Venables and Ripley 2002). Final models were constructed by hand based on the stepwise output followed by additional rounds of expert opinion for culling or re-including independent variables based on a variables interpretation and change in AIC value of the candidate model. While stepwise procedures have been criticized (i.e., Zuur et al. 2010), our approach is not entirely automated and we feel that the use of AIC (v. p-values) coupled with expert selection based interpretations

of the ecological relationships among a response and a candidate predictor(s) largely deals with these criticisms. Note that we do report p-values for the final included independent variables and for the model overall. While this is a subject of debate, we felt it appropriate for our exploratory purposes (*sensu* Murtaugh 2014).

To assist in the interpretation of variables in the final model, we estimated the relative contributions of each of the predictors to a model's total explanatory value. We used a classic (but recently much improved; Grömping 2006) approach that averages sequential sums of squares over orderings of regressors (Lindeman et al. 1980; Kruskall 1987). This produces estimates of each predictor's importance relative to the total amount of explained variance expressed as a simple percentage. These estimates consider both direct effects (i.e., correlations with the response) and the predictor variable's effect when combined with the other variables in the regression equation. The method averages over all possible orderings of predictors in a model, thereby dealing with multicollinearity (Grömping 2006).

Finally, we use conditional plots of partial residual to visualize these models (Larsen and McCleary 1972; Breheny and Burchett 2013). A partial residual plot is a graphical tool that shows the relationship between a given independent variable and the response variable, given that other independent variables are also in the model. The plot shows the value of the variable on the x-axis and the change in response on the y-axis, holding all other variables constant (by default, median for numeric variables and most common category for factors).

2.4.4 Assessment and interpretation

A key element of SEI monitoring and central to objectives three and five (assessing status) is the interpretation of results in a way that is both scientifically defensible and relevant to the management of Glacier streams. We follow assessment approaches and use terminology modified from Stoddard et al. (2006), Bennetts et al. (2007) and Mitchell et al. (2014), as these methods have become established in other federal monitoring programs. They are used in part by State of Montana (i.e., Suplee et al. 2005) and are beginning to coalesce within the NPS. Most importantly, Glacier has accepted our approach as a general and flexible framework for interpreting stream monitoring data.

In broad stroke, we compare our monitoring results to "assessment points" (defined below). We stress numeric over narrative assessment points to remove as much subjectivity from the process as possible. We interpret these comparisons in a collaborative way with park staff and management in the context of park management objectives, NPS I&M Division guidance, NPS resource management policies, and general ecological theory. We do not perform statistical tests of SEI data relative to an assessment point. Comparisons are instead whether an SEI response at a site or for the population of streams in the park, during a defined time period or over time, is above or below an assessment point, with no estimate of the statistical probability of this occurrence. Given continued development of our assessment approach since the publication of the SEI protocol in 2015, an overview of the process is provided here. Of note, some assessment strategies differ for temporal data (i.e., we use historical baselines as assessment points, especially for climate change driven patterns) from what is included here and will be presented in the sentinel site report (Schweiger et al. in preparation a). The next version of the SEI protocol will summarize all of these additions.

2.4.4.1 Assessment points: disturbance and ecological condition

To define classes in distributions of SEI data, we use assessment points (Bennetts et al. 2007). Assessment points are values in a response where scientists and managers have together agreed that they want to assess the status or trend of a resource relative to program goals, natural variation, or potential concerns. They establish boundaries between alternate states or classes in measures of disturbance or ecological response. Network monitoring and assessment includes a variety of types of assessment points, including management specified values, regulatory criteria, and well-defined ecological thresholds (see Schweiger et al. 2015). Assessment points may or may not correspond to patterns in ecological processes – although it is preferred that assessment points have ecological meaning. Nevertheless, even essentially arbitrary assessment points still have value as a basis for comparisons across streams or over time if they are well defined and explicit.

Disturbance classes

For measures of disturbance or stress (for example, general human use in and around a stream or water chemistry when beyond natural concentrations), we propose a set of four class labels originally developed in the Great Sand Dunes National Park and Preserve (GRSA) General Management Plan (GMP; NPS 2007): "negligible," "minor," "moderate," and "major." These loosely overlap with terms in the Glacier GMP (NPS 1999) used for management zones located across the park (Figure 10). However, the GRSA terms are more specific to the process of assessment, and while we suggest

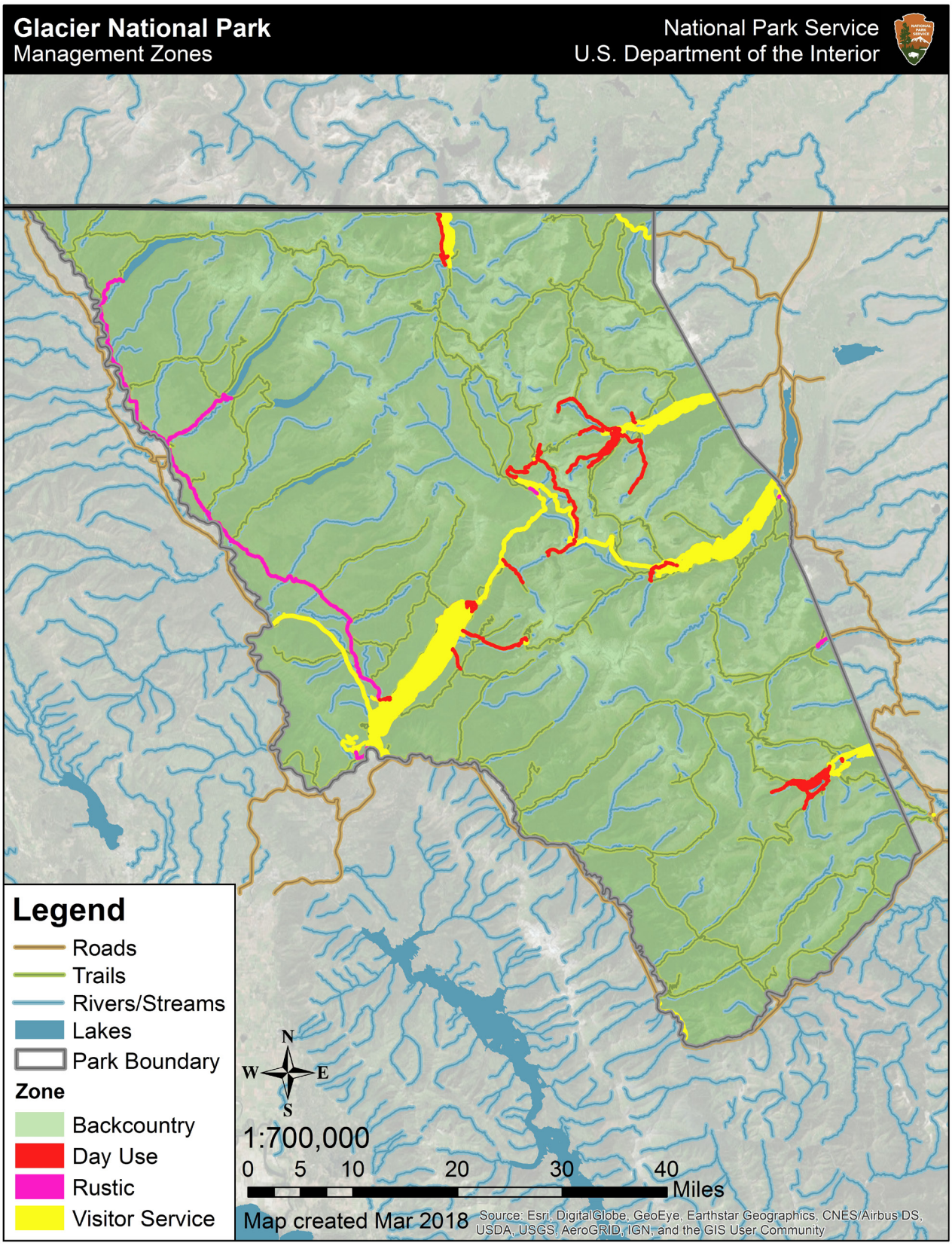


Figure 10. Map of Glacier National Park, showing four management zones: backcountry, day use, rustic, and visitor service. These terms crosswalk to class labels we use for disturbance and condition indicators of the park's streams, as detailed in Table 4.

crosswalks to the terminology from Glacier management zones, the GRSA labels are more appropriate for disturbance classes within monitoring results. "Negligible" defines a range of stress where an impact is barely detectable and/or would result in no measurable or perceptible changes to streams. This would be most typical of or representative of "backcountry" in the Glacier GMP. "Minor" describes a range of human disturbance where an impact is slight but detectable and/or would result in small but measurable changes in streams, but with all effects localized. This might most resemble disturbance in the "rustic" zone of Glacier, where primitive facilities and campgrounds occur and modest impacts on natural resources are tolerated. Importantly, we restrict "negligible" to cases where there is no measurable disturbance – true "zero" values. This may not be possible depending on the response (i.e., most water chemistry parameters cannot have a known true zero), and in these cases, the lowermost class for the measure would use the label "minor." "Moderate" defines the range where impacts are readily apparent and/or would result in easily detectable changes to streams, with most but not all effects localized. Within the Glacier GMP, this is similar to the "day use" zone, where visitors easily travel within a day from access points and higher levels of use are allowed. Finally, "major" applies to a range of stress where impacts can be severely adverse and result in appreciable changes to streams, with the effects often regionally important. This corresponds to the "visitor service" zone in the Glacier GMP that includes developed areas, paved roads, and campgrounds with potable water and sanitation facilities.

Ecological condition classes

For measures of ecological or biological condition, we use "pristine," "reference," "intermediate," and "non-reference," which are terms derived from the ecological assessment literature (Steedman 1994; Hughes 1995; Jackson and Davis 1995; Karr and Chu 1999; Davies and Jackson 2006; Stoddard et al. 2006, 2008). As with labels for disturbance classes, these conceptually overlap with terms in the Glacier GMP for management zones (NPS 1999; see Figure 10). First we use "reference" for classes or ranges that correspond to "good," intact, high ecological integrity. We use "non-reference" for "bad," degraded, low ecological integrity states. Reference corresponds to "rustic," and while the connotation is not ideal, "non-reference" might best match "visitor service." Where applicable, we use "intermediate" for condition range(s) in between "reference" and "non-reference." "Intermediate" condition might best crosswalk to the "day use" zone. We reserve a special case (see below) for the distribution of near "pristine" ecological condition values that correspond to negligible human disturbance. A pristine reference state is the desired condition in the Glacier "backcountry" zone.

Application of disturbance and ecological condition terms

The sets of terms for disturbance/stressor and biological response condition classes are applied across all types of assessment points. Assessment points may be set by Glacier resource management, be defined by regulatory criteria, be derived from ecoregional reference sites, or be based on well-defined ecological thresholds. We label classes on either side of these values using these disturbance or ecological condition terms, with the following clarifications. Following Stoddard et al. (2006, 2008), we restrict the use of the suite of terms that contain "reference" to the assessment of ecological or biological condition, or, in select cases, when there is a clear connection to ecological condition such as with synthetic physical habitat metrics. Thus, we will not label classes of a stressor, like high human disturbance or an excessive nutrient concentration, with "reference" or "non-reference"; rather, they are labeled as in a "major," "moderate," "minor" or "negligible" disturbance class. In cases where there is only one assessment point (meaning that there will only be two classes), we choose labels based on the type of assessment point, its intended use, and where it falls in the distribution of values for a response. For ecological response, this is usually "reference" and "non-reference" (omitting intermediate and pristine reference). For disturbance/stressors, this is usually "major" and "minor." Finally, a key part of the NPS mission statement is to maintain resources "unimpaired." However this terminology is also used in the Clean Water Act (CWA), where regulatory criteria are defined that set impairment (or when a waterbody is not meeting its designated uses as set by the Montana DEQ, the EPA and/or a Tribal Nation). However, as discussed further in the following section, we do not use the CWA term "impairment" in a regulatory context in our assessments. Rather we equate regulatory criteria as corresponding to "major" stress.

Relationship to Clean Water Act regulatory terminology

Network stream monitoring is designed to document the ecological integrity or capacity of park streams to support and maintain a balanced, integrated, and adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of natural habitats of the region. We believe this integrates well with the NPS Organic Act mission to conserve all resources "unimpaired for the enjoyment of future generations." To better

interpret stream monitoring results, we utilize the framework and criteria developed by EPA and states under the CWA, but our assessment is not formally tied to the CWA nor do we use the term "impairment" as defined by the CWA or determine whether a "designated use" has been attained.

NPS does not have regulatory authority under the CWA over streams in parks. Therefore our network SEI assessment is conducted outside of regulatory context. Any comparisons we make using SEI or partner data to state or federal regulatory criteria do not include a statement as to whether a beneficial designated use was attained. Interpretation of water chemistry standards or 303(d) impairment decisions are beyond the scope of our analyses and are not provided here. SEI data are nevertheless useful for understanding and evaluating whether park streams are in good condition or impaired either under the NPS Organic act or under the CWA. If requested and appropriate, the network (through Glacier) will provide them for this purpose.

2.4.4.2 Assessment strategy for Glacier 2007–2009 data

A summary of our assessment methods as applied to Glacier SEI 2007–2009 data follows. See also Schweiger et al. (2015). Where methods vary meaningfully from the following, we include additional detail in results sections below.

Identify and prioritize assessment points

Stream monitoring in Glacier has the benefit of a spectrum of existing assessment points developed by several collaborators for a variety of circumstances. Priorities for application of these options can vary with a given response, and in many cases, one or more of these options do not exist. In general, however, the hierarchy is as follows: 1) Glacier management derived assessment points (which may include any of the following), 2) state/federal/tribal nation regulatory criteria, 3) ecological thresholds, and 4) "ecoregion" assessment points derived from reference site data within and around Glacier. Note that while ecoregion assessment points are the last in the hierarchy, in many cases these are the only assessment point(s) available and they are thus often widely used. Details regarding the definition and application of regulatory criteria and ecological thresholds are in Schweiger et al. (2015) and Appendix D.

Ecoregional assessment points

We use a methodology known as the "reference site approach." This approach is well accepted and common in state and other federal monitoring programs (Stoddard et al. 2006, 2008; Suplee et al. 2005; Hubler 2007; Kusnierz et al. 2013). Key assumptions include that reference sites are ecologically similar to SEI sites and that stream monitoring methodologies used across sites are comparable – this is why the SEI protocol is based on methods common to our state and federal partners. Use of properly defined reference sites help assure that reference state assessment points are based on a "natural" condition shaped by a broad spectrum of drivers, such as climate, geography, or successional dynamics. In contrast, non-reference sites are structured by both direct and indirect anthropogenic stress and natural variation and thus confound these two types of drivers. Intermediate states tending towards the reference end of the spectrum are influenced increasingly only by natural drivers, and vice versa.

The process for using ecoregional assessment points includes five steps: 1) define relevant reference sites from the ecoregion(s) a park is embedded in, 2) collect data from these sites for the indicators being assessed, 3) classify the appropriate context (least or minimaly disturbed, see below) for the park, 4) set percentile-based thresholds in the distributions of the reference site indicator data following EPA guidelines, and 5) compare SEI data to the disturbance or condition classes defined by ecoregional assessment points.

Glacier is embedded in the Northern Rockies and Canadian Rockies ecoregions (see Figure 8). Monitoring sites on streams in these ecoregions expected to be in a reference state are identified by Montana DEQ and EPA. Given our large and representative sample of Glacier's streams in 2007–2009, we augment the population of ecoregional reference sites by applying the Montana DEQ methods to SEI sites. This increases the sample size and helps link assessment points and reference conditions to the population of reference streams in Glacier. The Montana DEQ and EPA methods for selecting reference sites use a suite of variables that filter candidate sites based on their physiochemical and landscape context. Filters include bank erosion, sediment deposition, grazing impacts, cumulative impacts from multiple causes, site-specific data sufficiency, impacts from land-use based on the proportion of agriculture, numeric water-quality standards exceedances for heavy metals, impacts from mines, road density, and timber-harvest intensity (Suplee et al. 2005). When applied to Glacier SEI sites, 38 (out of 49) sites were classified as in reference condition, and 11 in a non-reference state (Appendix E). In select cases, Glacier SEI expected reference condition sites are the only ones available for a given indicator. Note that when these methods were applied to SEI sites, they create *a priori*, or expected, reference classifications that are not necessarily the

same as assessments based on the full weight of our monitoring data for Glacier streams as presented in this report. Our final assessments reflect more detailed data, evaluation of a response to the gradient in human disturbance vs. the ordinal classification of Montana DEQ, and for select cases, a modeling process that predicts ecological response specific to the streams of Glacier. As of 2016 there were 77, 120, and 142 reference sites available for water chemistry, habitat, and biological data (respectively) from partner and SEI reference sites (most of these sites include data from a relevant time period for this report).

Next we set the reference context for Glacier following guidance from the EPA (Stoddard et al. 2006, 2008) and as confirmed by Glacier resource management. Reference context is based on the degree of historical and extant disturbance in and around a park and may be a "least disturbed condition" (LDC) or a "minimally disturbed condition" (MDC). LDC applies when there has been historical human disturbance in and around a park or where a park is nested within a largely human-modified matrix. MDC applies where there has been no measureable stress beyond diffuse large scale impacts (i.e., low level nutrient deposition) and includes parks surrounded by wilderness area or other low use protected landscapes (Stoddard et al. 2006, 2008). The choice of an MDC or LDC alters the percentile values at which assessment point values are set in the distribution of an indicator at reference sites (see below). The choice of a whether a park is in an MDC or LDC context is an important step in the assessment process and should ultimately be made by a park in consultation with the network. We propose in this report that the appropriate context for Glacier is an MDC, given the park's context and large size. An MDC "sets the bar high" for the assessment of SEI data in Glacier (Hughes et al. 1986; Hughes 1995; Stoddard et al. 2006; see also Bailey et al. 2004). Figure 11 and Table 4 illustrate the general relationship between assessment points that define disturbance classes and the corresponding condition states.

Assessment points in an MDC context are based on percentile values from Stoddard et al. (2006, 2008). The percentile values used in an MDC are more conservative than those applied in an LDC context – in other words, it is "harder" for a response at a Glacier SEI site to be assessed as in a reference state than it would be if we assumed an LDC was the correct context for the park. For responses that increase with decreasing condition (like most water chemistry parameters or the HDI; Table 4) we use the >95th percentile for major disturbance (stressors) or non-reference (ecological condition metrics) class. We use a <75th percentile for minor disturbances (stressors) or a reference condition (ecological condition metrics). For responses that decrease with decreasing condition (like most bioassessment metrics), we use the <5th percentile for major disturbance (stressors) or non-reference (ecological condition metrics) thresholds. We use >25th percentile values for minor disturbances (stressors) or a reference condition. Values in between these percentiles fall in a moderate stress class and an intermediate ecological condition. Note that we reserve negligible disturbance as a special case at a true zero value (or the 0th percentile). This zero value must be reliably estimable and conceptually sensible.

Percentile based ecoregional assessment points are arbitrary. However they are well defined, explicit, allow for quantitative comparisons over time, and are in use by several other long-term monitoring programs (Stoddard et al. 2006, 2008; EPA 2015) and Montana DEQ (Suplee et al. 2005). We consider them baseline values to use as we develop more meaningful ecological assessment points and/or as we work with park management to define relevant management assessment points for stream protection in the park. They also place Glacier in the context of its surrounding ecoregions – how do streams in the park compare to reference streams in the largely wilderness areas surrounding the park? They have the important strength of being derived from empirical distributions that account for natural variability across a wide variety of stream types in reference conditions relevant for Glacier.

Predicting pristine ecological response

For our park-scaled bioassessment measures (i.e., the Glacier MMI for macroinvertebrates or diatoms), we develop more specific and meaningful assessment points by modeling the relationship between disturbance and ecological response (see Figure 11). We predict MMI scores at assessment point values in HDI, including a value of zero or negligible disturbance. We define the predicted response at HDI = 0 as a "pristine reference condition" and feel that this has real ecological meaning as it is based on an absence of significant human disturbance, not an essentially arbitrary (but useful) percentile. We can estimate the natural variation around each predicted condition assessment point using the 95% prediction interval around each predicted value. A prediction interval takes into account the variability in the conditional distributions of a predicted MMI assessment point as well as the uncertainty in our estimate of the conditional mean value (both of which play a role in the ability to predict an MMI score at HDI = 0). However for simplicity we use the centroid of the prediction interval.

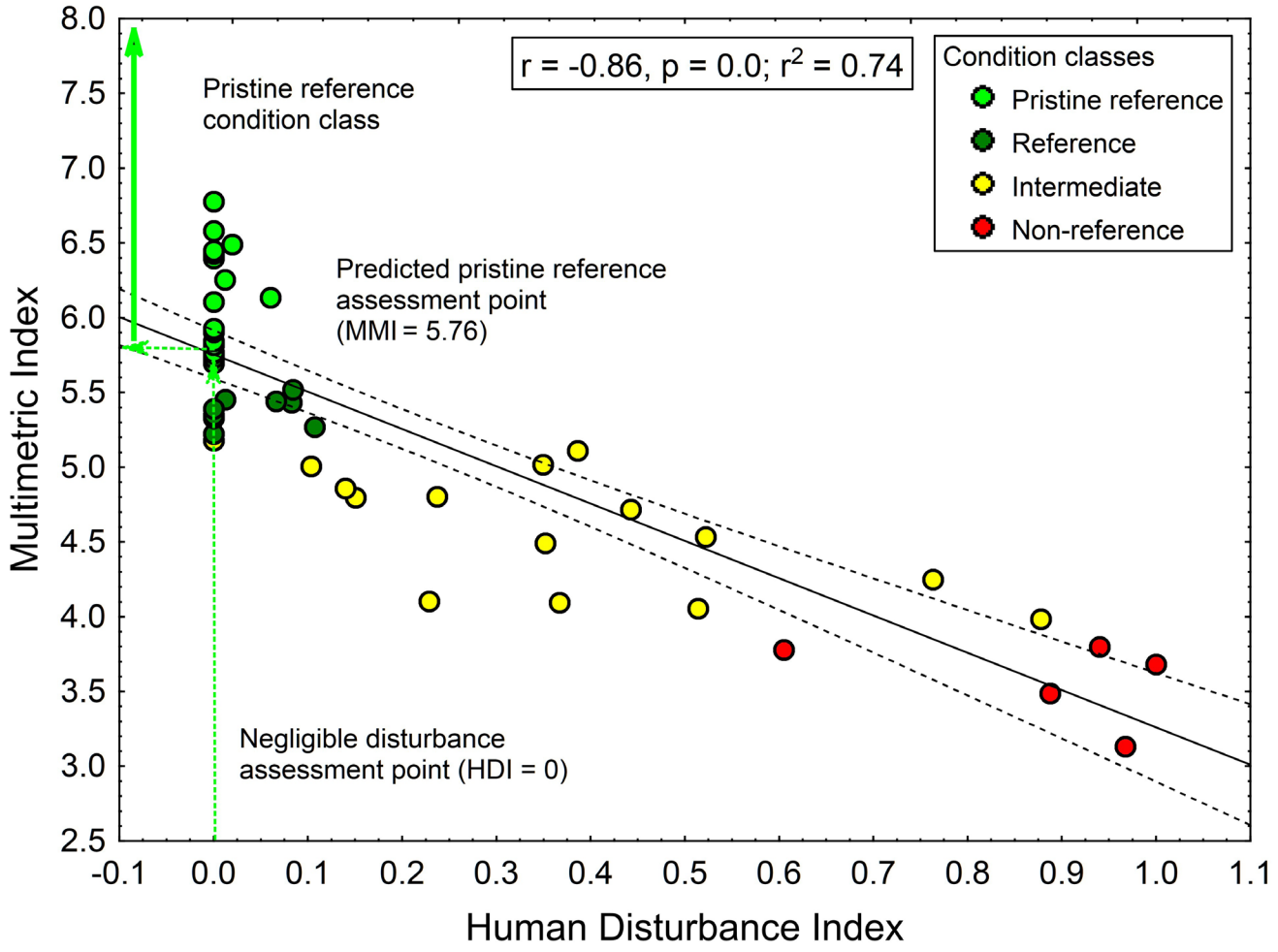


Figure 11. Illustration of relationship between human disturbance (HDI) and multimetric index values. Using our Glacier-specific macroinvertebrate multimetric index as an example, an HDI value of 0 (indicating negligible disturbance) the predicted MMI value is 5.76 (as the simple linear fit), which then forms the assessment point for the pristine reference condition class. Increasing disturbance values likewiwse predict reference then nonreference condition classes (not shown). Note these data are actual MMI results for Glacier National Park.

Table 4. Stream disturbance classes and assessment point values related to stream ecological integrity reference condition classes. Disturbance class terminology is from the Great Sand Dunes National Park and Preserve General Management Plan.

Disturbance class	Assessment point[1]	Ecological condition class and Glacier National Park General Management Plan terminology	Description
Major	Value in the top 95th percentile	Non-reference; "Visitor service"	Ecological state is "bad," degraded, and/or with "low" ecological integrity.
Moderate	Value between the 95th percentile and 75th percentile	Intermediate condition; "Day use"	Ecological state between reference and non-reference.
Minor	Value <50th percentile	Reference condition; "Rustic"	Ecological state is "good" but allows for a degree of physical, chemical, and biological alteration.
Negligible[2]	Value ≤ 0	Pristine reference condition; "Backcountry"	Ecological state is "pristine" with no measurable human impact.

[1]Response illustrated here increases with decreasing condition (i.e., Human Disturbance Index or most water chemistry parameters) and assumes a minimally disturbed context landscape. For a response that decreases with decreasing condition, the percentile values are the inverse of those shown here (5th and 25th percentiles).

[2]Negligible disturbance requires a response that can logically be zero and/or is measurable and reportable at a zero value.

2.4.4.3 Summary condition tables

Select Glacier SEI results are summarized in "summary condition" tables that include a brief description of our indicators of stream ecological integrity, summaries of the status in the condition of these indicators, and our confidence in the result (note: we don't analyze trends in this report – see Schweiger et al. (in preparation a)). They are accompanied by simple graphic symbols that visualize important features of summary condition statements. Table 5 gives the legend for all summary condition tables in this report.

Summary condition statements are important for rapid integration into park resource management and interpretation. However, they are a simplification of details presented in our full results and discussion sections and should be used with caution. They are most reliable when we have assessment points for a given measure or metric, especially when these have either a direct connection to ecological processes, management of streams, or have relevancy from other studies or research.

Table 5. Symbology and terminology for summary condition tables used in this report.

Condition status		Confidence in assessment	
Symbol	**Description**	**Symbol**	**Description**
	Non-reference condition Major disturbance		High
	Intermediate condition Moderate disturbance		Medium
	Reference condition Minor disturbance		Low
	Pristine reference condition Negligible disturbance	–	–
	Unknown or indeterminate condition	–	–

2.4.5 Data availability

Data presented in this report and additional figures, tables, and model output are available from the Rocky Mountain Network (ROMN). Quality checked data are located on the NPS long-term data archive website, the Integrated Resources Management Applications (IRMA) portal. Data products have been bundled into an IRMA project, "Glacier National Stream Ecological Integrity 2007-2009 status report products and data package," available at: https://irma.nps.gov/DataStore/Reference/Profile/2253545

Additionally specific SEI data elements and summary tables are accessible as defined below.

- ROMN SEI Access Database – Glacier National Park 2007-2009: https://irma.nps.gov/DataStore/Reference/Edit/2252546
- ROMN SEI MacroInvertebrates Access Database – Glacier National park 2007-2009: https://irma.nps.gov/DataStore/Reference/Profile/2253276
- ROMN SEI Discrete Water Quality data - Glacier National Park 2007-2009: https://irma.nps.gov/DataStore/Reference/Profile/2253607
- Water chemistry lab data are available for download on the Environmental Protection Agency STOrage and RETrieval and Water chemistry eXchange (STORET & WQX) Data Warehouse: (http://www.epa.gov/storet/dw_home.html). An IRMA reference with instructions to access ROMN water quality/chemistry data: https://irma.nps.gov/DataStore/Reference/Profile/2253549
- Continuous Water Chemistry Data are available for visualization and download on the "NPS Continuous Water Data – Aquarius" web portal (https://irma.nps.gov/aqwebportal/). An IRMA reference with instructions to access ROMN SEI continuous water quality/chemistry data is at: https://irma.nps.gov/DataStore/Reference/Profile/2253551



Figure 12. Human-caused disturbance on Divide Creek in Glacier National Park, 2007.

3 Results and Discussion

3.1 Organization of the results and discussion section

The following sections present results and interpretation of Glacier SEI data collected across 49 long-term stream monitoring sites from 2007 to 2009. We organize this section by response measure type (i.e., human disturbance, water chemistry, habitat, bioassessment), prefaced by the ecological setting of climate context and stream length. We include both results and interpretation/discussion of important patterns in the data. Each section begins with a summary condition paragraph and overview of the response measure itself, and then a full summary condition table.

We order the results and discussion section logically, beginning with results from our estimates of the stressors and drivers of ecological condition in the streams of Glacier National Park. We conclude with the bioassessment models built from these supporting data. However, given our emphasis on bioassessment in interpreting overall stream ecological integrity, the order of importance to many readers may be the "other way around" – park resource managers in particular may want to begin with the last chapter (bioassessment) in the results and discussion section and/or focus on the Executive Summary, or the summary condition tables.

As a reminder, a condensed version of results for all indicators is available in the Executive Summary's summary condition table.

3.2 Sample events

From July of 2007 to October of 2009 we established 49 unique long-term stream monitoring sites in the park (see Figure A1 for a map of all sites labeled by site name). Most sites were selected by the survey design and only sampled once in this three year period. Twelve sites were sampled multiple times to provide estimates of short-term variance in our results or as the initial events in our sentinel monitoring. For sites with replicates, data used for most analyses presented here are taken from the sample event at the site that we feel is most representative of the site and that was surveyed by the most experienced crew. Overall we conducted 75 sample events that included all methods at these sites during the three year period presented in this report. An additional 14 sentinel sample events that did not include all methods (i.e., only water chemistry was sampled) were completed over these years. From 2010 to 2016 an additional 28 full and 77 sentinel events were conducted at four sentinel sites in the park – these data are reported in our sentinel site report (Schweiger et al. in preparation a).

3.3 Climate context

Climate plays an important role in stream ecology and in the interpretation of patterns in stream condition (i.e., Colwell et al. 2012). Given climate's dynamic nature it may be more relevant to analyses of trend; however, we still present basic summaries of climatic conditions during the stream survey to help understand the context of our data. Importantly these are only brief summaries and they are taken from a limited number of stations in the park.

The climate of Glacier is characterized by a cool season stretching through fall, winter, and spring, and summers with warm days and cool nights (Pederson et al. 2010). The Rocky Mountains are oriented perpendicular to the prevailing westerly winds in the park, creating extreme east–west climate gradients in the park and large amounts of snow at high elevations (Davey et al. 2007). It is frequently 10 to 15 degrees cooler at higher elevations (NPS 2006a). Glacier's western valleys generally receive more rainfall than its east side, where strong winds and sunny days predominate (NPS 2006a).

3.3.1 Air temperature

Mean deviations from 30 year normal (1980–2010) maximum and minimum temperatures at the primary east and west side weather stations in Glacier during 2007 to 2009 are shown in Figure 13. The East Glacier station had colder maximum (summer) and warmer minimum (winters) than the 30 year normal. The West Glacier side station shows warmer or average maximum temperatures, with a notably warm summer in 2007 followed by average summer and colder winters in 2008 and 2009.

3.3.2 Precipitation

Patterns in total annual precipitation at the same two weather stations in Glacier – East and West Glacier COOP – for the 2001 to 2016 water years (this longer time frame was chosen to better bracket the 2007–2009 survey period) are shown in Figure 14. These suggest that on the west side of the park, precipitation was below or near normal in 2007–2009. The east side station shows a more pronounced drought period through 2007 and 2008, with a return to more average precipitation in 2009. While single year or survey period specific results are not available, Monahan and Fisichelli (2014) show that the 10 year period from 2003 to 2012 had extreme values (meaning in the 95th or 5th percentile relative

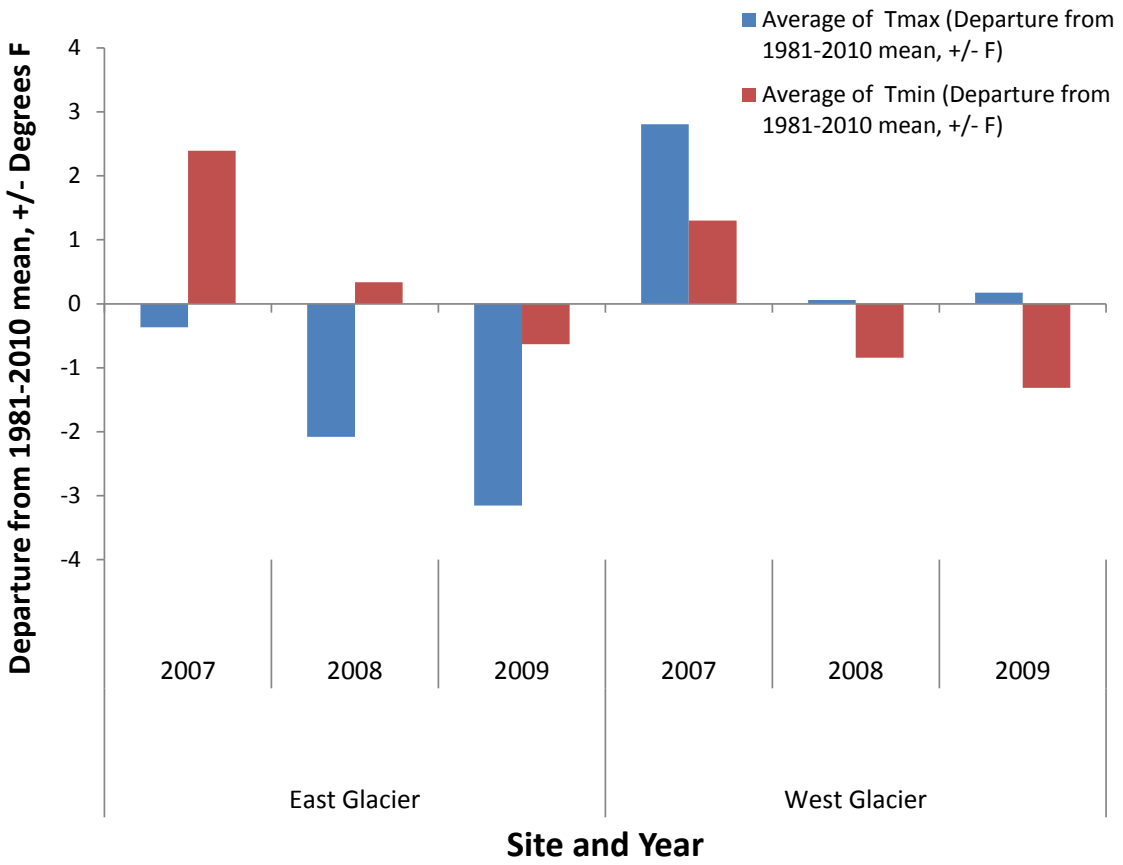


Figure 13. Deviation in maximum and minimum air temperatures during 2007–2009 water years from 30 year average (1981–2010) at the East and West Glacier COOP weather stations, Glacier National Park.

to 10 year moving window averages from 1901 to 2012) in minimum temperatures of the coldest month (i.e., warmer winters), mean temperatures of the wettest quarter (i.e., warmer springs), and the mean temperature of the coldest quarter (i.e., warmer winters). Winters on average were also extremely dry.

3.3.3 Hydrologic regime: reflection of climate

Hydrology, or the amount and timing of stream flow, is one of the most important aspects of stream habitat and a key long-term monitoring response for the SEI protocol. It is one of the best reflections of climate's interaction with streams. Hydrographs from long-term USGS gauges on the west (North fork of the Flathead River) and east (Swiftcurrent Creek) sides of the park for the 2007–2009 water years are shown in Figure 15 and Figure 16. These plot daily discharge by water year and the mean daily values for the historical period of record (1980–2010). They also include the median or midpoint of total discharge for these time periods. While they are site specific these two basins are somewhat representative of discharge at other sites. These data suggest that 2007 and 2009 were dry years, with an early runoff in 2007 on the North Fork. Stream flow was more typical in 2008. Discharge patterns were similar at Swiftcurrent, with lower flows in 2007 and (marginally) in 2009. While there are complex temporal dynamics (i.e., lags), these patterns generally reflect what we see with the climate data.

Overall, climate patterns over the three year survey period were at first hot and dry, with a return to more typical conditions in 2009. Importantly these are short term patterns that must be viewed with caution. They are in the context of a pronounced shift in climate drivers in the park and the western United States more generally (Pederson et al. 2010). Changes in stream hydrology due to climate changes over the past 50 years in the West are well documented (Barnett et al. 2008) and these changes are expected to continue. Physical, chemical, and biological characteristics of aquatic ecosystems act as indicators of impacts due to climate change (McKnight et al. 1997). Even modest temperature increases in the western United States may cause significant changes to the hydrologic cycle, manifested as earlier snowmelt, earlier ice-out on lakes, reduced summer base flow (Dettinger et al. 2004), a lower snowpack volume at lower to mid elevations

(Knowles et al. 2006), and increased flooding due to rain-on-snow events in winter (Heard 2005), especially when coupled with dramatic precipitation events. Hydrographs will likely shift to earlier floods. These changes will, in turn, likely affect the seasonal dynamics of stream and riparian biota (Palmer and Bernhardt 2006). As summarized in Ashton (2010) climate change may significantly impact aquatic resources in Glacier and likely make it more difficult to achieve water chemistry standards nationwide (Field et al. 2007).

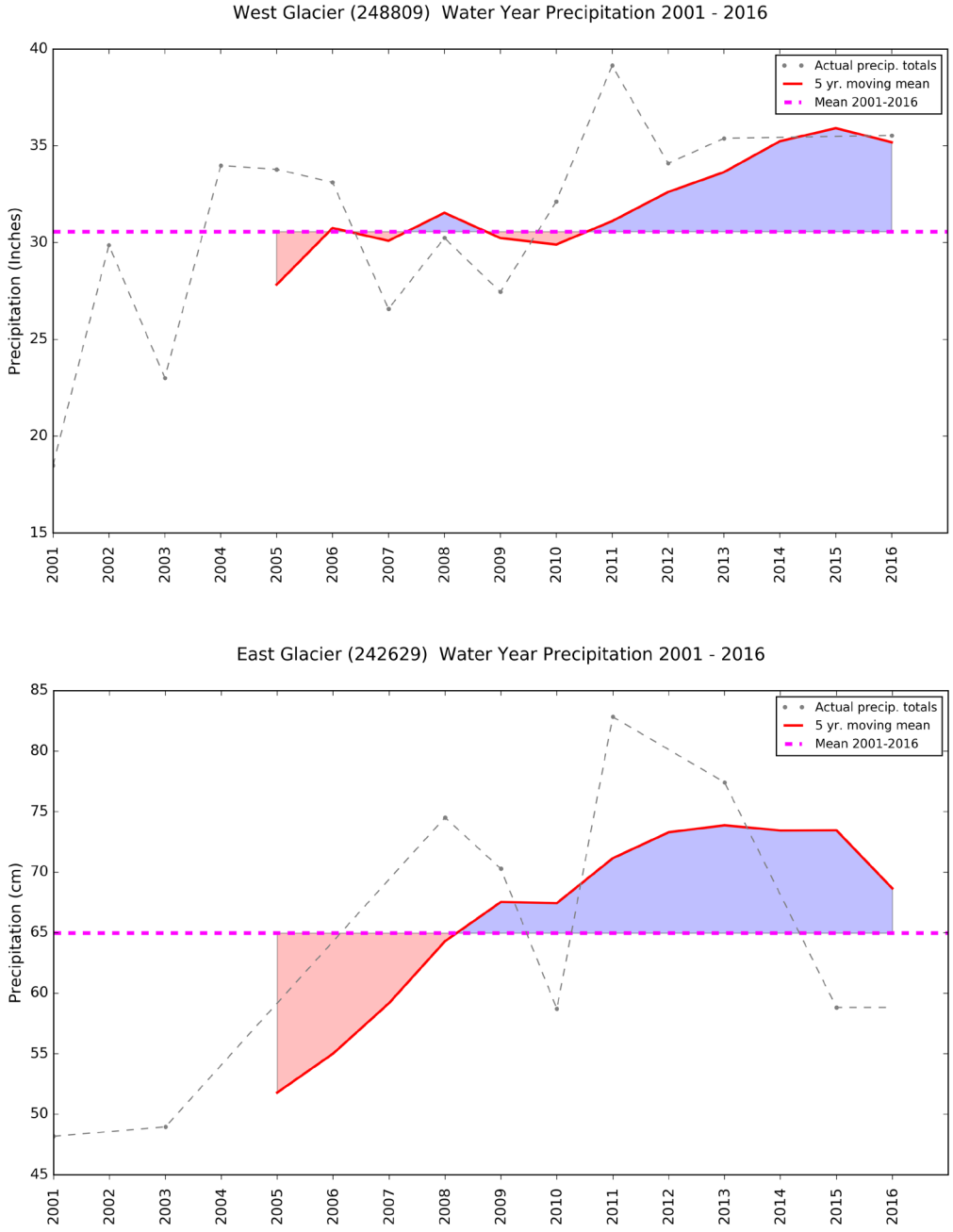


Figure 14. Running 5 year mean (solid red line) and annual precipitation (lightly dotted gray line) at the West (top) and East (bottom) Glacier COOP weather stations for the 2001 to 2016 water years in Glacier National Park. The period mean is also shown with the heavily dotted pink horizontal line. The deviation from this period mean is given with orange (negative) and blue (positive) shading.

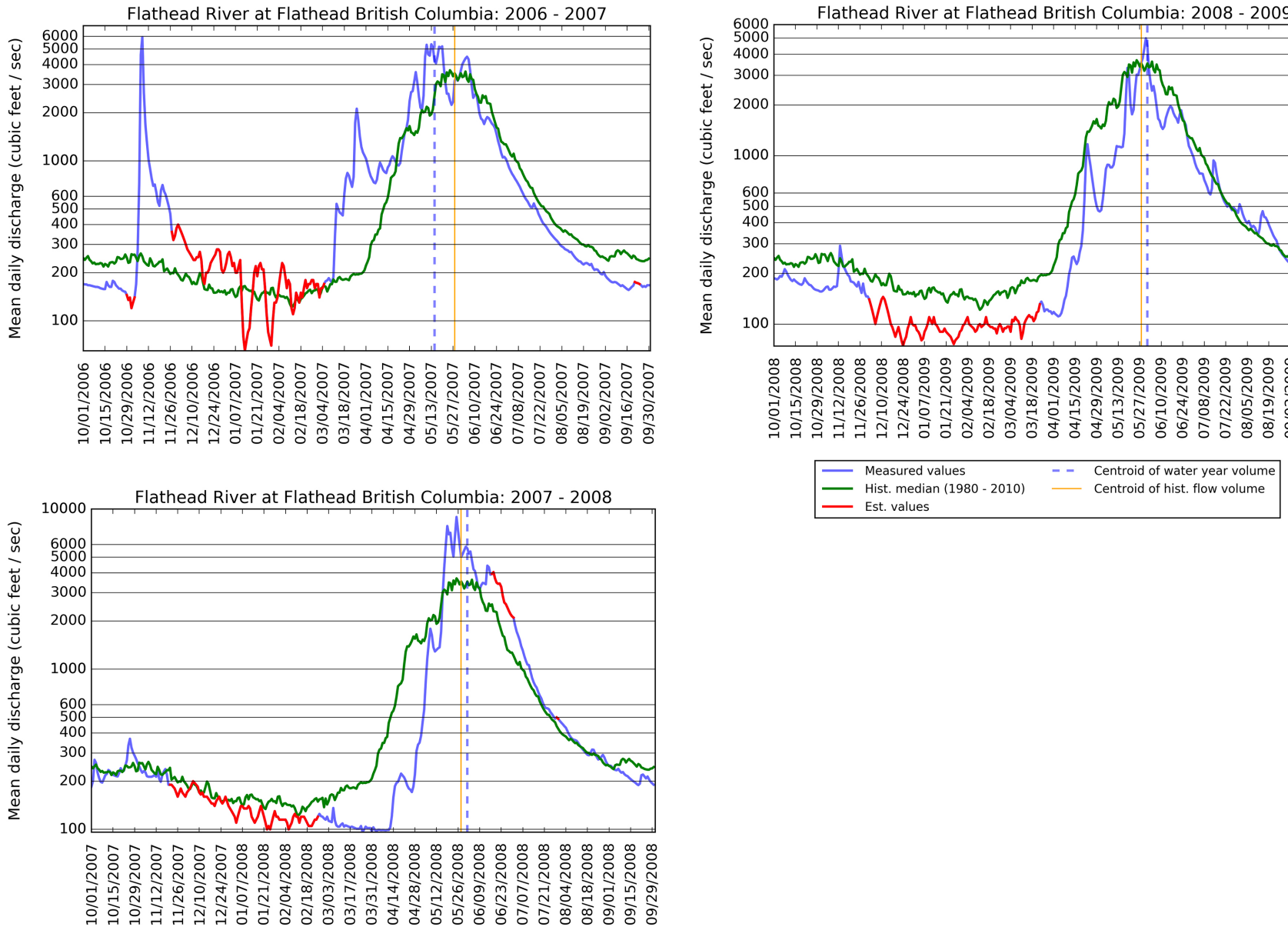


Figure 15. Hydrographs for 2007–2009 water years at the North Fork USGS gauge on the west side of the Glacier National Park. Figures include measured and estimated values for the current water year (heavy blue and red lines), the 30 year normal discharge (light green line), and the midpoints of the current and historical hydrograph (vertical orange and dotted blue lines). Discharge in ft3/sec is on a log scale. Graphics were produced in the Climate Analyzer (Walking Shadow Ecology 2017).

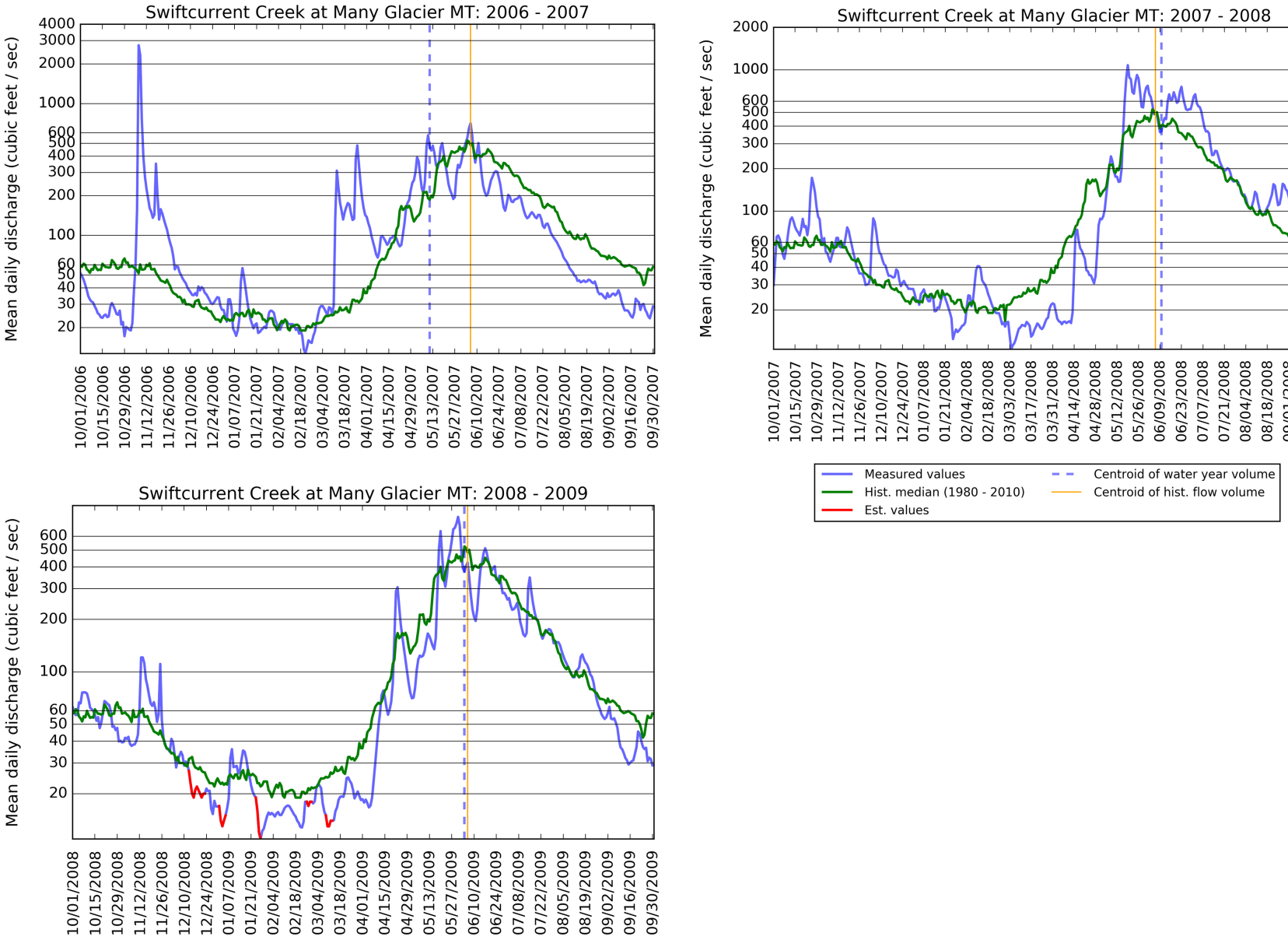


Figure 16. Hydrographs for 2007–2009 water years at the Swiftcurrent Creek USGS gauge on the east side of the park. Figures include measured and estimated values for the current water year (heavy blue and red lines), the 30 year normal discharge (light green line), and the midpoints of the current and historical hydrograph (vertical orange and dotted blue lines). Discharge in ft3/sec is on a log scale. Graphics were produced in the Climate Analyzer (Walking Shadow Ecology 2017).

3.4 Stream length

An important component of a survey-based approach to monitoring is an estimate of the extent of the resource of interest (Olsen and Peck 2008). This explicitly defines what our status estimates pertain to. The extent of streams is itself often used as an indicator of the condition of the resource across a landscape. Many functions are more secure when stream networks are extensive, well connected, and buffered from disturbance.

We lack estimates of the historical extent of streams in Glacier, thus we do not know the historical or natural range of variability in stream length. Therefore our interpretation of these results is limited and we use extent estimates as baseline assessment points for future monitoring.

To address Objective 1 (length of streams in the park) across the entirety of Glacier, we use two data sources: 1) the most current remotely sensed data, and 2) our site evaluation data from the 2007–2009 SEI survey. Survey data take advantage of site level assessment inferred to all streams in the park using properties of the survey design.

Site evaluation was conducted for 89 survey sites. These included the first 50 (the order of sites is a critical attribute set by the GRTS design) from the base sample list and the first 39 on the oversample list. Note that we use sites in order from the oversample list for replacement, "skipping over" sites from several of the base small panels (when done correctly this is an acceptable practice; T. Olsen pers. comm.). Site evaluation determined if a site was on a perennial stream and if it was safely sampleable, with no compliance issues. The evaluations were conducted independent of any information contained in NHD (USGS National Hydrography Database) using standardized procedures and data recording forms. Sites were placed into four categories: target sampleable (40 sites that were sampled during 2007–2009), target office (24 sites that were sampleable perennial streams but were not sampled during 2007–2009), non-sampleable (nine sites that were true streams but that had safety or compliance issues and thus were not sampleable during 2007–2009), and non-target (16 sites that were not perennial streams). To construct extent estimates of the target population and the sampled population, we collapsed the evaluations into two sets of classes: 1) perennial sampleable plus perennial and non-sampleable vs. non-perennial, and 2) perennial and sampleable vs. non-perennial plus perennial but non-sampleable. The first set describes the target population as it includes non-sampled perennial stream as target. Extent estimates from this are important as they describe the total length of perennial stream in the park in 2007–2009. The second set describes the sample population as it excludes from the target designation sites that were streams but were not sampleable. Extent estimates from the second set are important as they describe the resource to which all condition estimates in this report pertain.

We used the properties of the survey design to generate design-based estimates of stream length within these two categories (Table 6a-d). The design-based estimates for the target and sampled population of streams in Glacier during 2007–2009 include a confidence interval generated using the local neighborhood variance estimator that should always accompany any interpretation of these statistics. Moreover, the design-based estimates are only a snapshot of stream extent during 2007–2009; they reflect the hydrologic and geomorphic conditions during this period and most importantly the constraints imposed by sampleability (access and safety).

The NHD data indicated that there were about 2362 km of perennial stream in the park (1464 miles). Our survey suggested that from 410 to 945 km of this length were actually not stream (the bounds on the non-target portion of the target population) and that the true length of stream in the park might be closer to 1684 km (1044 miles) – this is about 71% of what NHD included. Using the design-based estimates of the extent of sampleable stream, another 314 to 373 km were stream but were not sampleable (the difference between target and sample population extents), giving a mean estimate of 1340 km (831 miles) of sampleable perennial stream in the park. This is about 57% of what the NHD data suggest is the total length of streams in the park. This last number (or its upper and lower bounds) is the one to which all SEI survey based statistics apply.

Patterns across stream order are typical for high relief landscapes like Glacier, with over 56% of the target population as first or second order streams. Most (16) of the sites that were non-target within the target population (i.e., they were not perennial streams) were 1st or 2nd order (one was 3rd order, but this was also a small stream). They were mostly high altitude streams or tributaries to larger channels. These stream types are naturally ephemeral or intermittent and we do not have sufficient data or model results to suggest that is an indication of a problem. However, it will be interesting to see if this number changes over time and if we can connect this to climate-change driven shifts in precipitation or continued loss of glaciers and their meltwaters from the park (Heard 2005).

Table 6a. Glacier National Park stream extent estimates using design-based totals for **target and sample** population. National Hydrography Dataset (NHD) values are for all perennial[1] streams.

Population	Category[2]	N	%	L CI (%)[3]	U CI (%)[3]	Length (m)	NHD (m)	LCI (m)	UCI (m)
Target Pop.	NT	16	28.69	17.37	40.02	677754.67	–	410233.30	945276.04
Target Pop.	T	73	71.31	59.98	82.63	1,684,330.64	2,362,085.31	1,416,809.27	1,951,852.01
Sample Pop.	NT	25	43.25	30.66	55.83	1021515.11	–	724244.86	1318785.36
Sample Pop.	T	64	56.75	44.17	69.34	1,340,570.20	2,362,085.31	1,043,299.95	1,637,840.45

[1] Includes artificial path centerlines for larger rivers.

[2] Category: T = "target"; NT = non-target".

[3] L/U CI = lower or upper bounds of 95% confidence interval.

Table 6b. Glacier National Park stream extent estimates using USGS National Hydrography Database (NHD) non-perennial and perennial[1] extent by stream order.

Stream order	Length of non-perennial stream (m)	% of total	Length of perennial stream (m)	% of total
1	1905417.34	93.86	937025.03	39.67
2	113471.26	5.59	667276.99	28.25
3	3016.94	0.15	459038.23	19.43
4	6279.77	0.31	211578.9	8.96
5	1204.1	0.06	44954.28	1.9
6	774.76	0.04	42211.88	1.79
Total	2,030,164.17	–	2,362,085.31	–

[1] Includes artificial path centerlines for larger rivers.

Table 6c. Glacier National Park stream extent estimates using design-based target population extent by order.

Stream order	Category[1]	N	% of order class	L CI (%)[2]	U CI (%)[2]	Length (m)	NHD (m)[3]	LCI (m)[2]	UCI (m)[2]
1	NT	8	52.76	31.57	73.95	494377.35	–	295789.84	692964.86
1	T	9	47.24	26.05	68.43	442647.68	937025.03	244060.18	641235.19
2	NT	7	23.21	8.24	38.18	154873.83	–	55002.89	254744.76
2	T	17	76.79	61.82	91.76	512403.16	667276.99	412532.23	612274.10
3	NT	1	6.21	0.00	16.24	28503.50	–	0.00	74551.06
3	T	19	93.79	83.76	100.00	430534.74	459038.23	384487.17	459038.23
4	NT	0	0	–	–	0	–	–	–
4	T	13	100.00	100.00	100.00	211578.90	211578.90	211578.90	211578.90
5	NT	0	0	–	–	0	–	–	–
5	T	8	100.00	100.00	100.00	44954.28	44954.28	44954.28	44954.28
6	NT	0	0	–	–	0	–	–	–
6	T	7	100.00	100.00	100.00	42211.88	42211.88	42211.88	42211.88

[1] Category: T = "target"; NT = "non-target."

[2] L/U CI = lower or upper bounds of 95% confidence interval.

[3] NHD = USGS National Hydrography Dataset.

Table 6d. Glacier National Park stream extent estimates using design-based sample population extent by stream order.

Stream order	Category[1]	N	% of order class	L CI (%)[2]	U CI (%)[2]	Length (m)	LCI (m)[2]	UCI (m)[2]
1	NT	11	68.30	47.73	88.86	639952.20	447250.74	832653.65
1	T	6	31.70	11.14	52.27	297072.84	104371.39	489774.29
2	NT	11	47.51	27.84	67.18	317048.57	185790.28	448306.86
2	T	13	52.49	32.82	72.16	350228.42	218970.13	481486.71
3	NT	2	12.73	0.00	27.42	58418.07	0.00	125852.08
3	T	18	87.27	72.58	100.00	400620.16	333186.15	459038.23
4	NT	0	0	–	–	0	–	–
4	T	13	100.00	100.00	100.00	211578.90	211578.90	211578.90
5	NT	1	13.56	0.00	35.26	6096.28	0.00	15853.04
5	NT	0	0	–	–	0	–	–
5	T	7	86.44	64.74	100.00	38858.00	29101.24	44954.28
6	NT	0	0	–	–	0	–	–
6	T	7	100.00	100.00	100.00	42211.88	42211.88	42211.88

[1] Category: T = "target"; NT = non-target."

[2] L/U CI = lower or upper bounds of 95% confidence interval.

NHD data indicate there are 2030 km (2662 miles) of non-perennial stream in the park. This is 85% of the total stream resource (perennial + non-perennial) in the Glacier NHD data. This is comparable to the western United States, where around 73% of the total stream resource is non-perennial (Olsen and Peck 2008). Olsen and Peck (2008) present results of a dedicated survey of non-perennial streams in NHD West-wide. Their results suggest around 7% of the non-perennial streams were actually perennial. Because a survey of the non-perennial component of the Glacier NHD was beyond our means, we must assume that the incorrectly classified component of non-perennial that is actually perennial stream in Glacier is also around 7%. Both truly non-perennial and perennial streams classified as non–perennial represent a stream resource that was not made available to the survey and was thus not included in SEI monitoring. While sampling intermittent or ephemeral non-perennial systems is challenging and would require another protocol, this habitat type likely has relevant ecological conditions and important functions not currently included in SEI monitoring. Future work should address this issue, especially if more drainages become non-perennial, as is expected with climate change (McKnight et al. 1997; Dettinger et al. 2004).

3.5 Human disturbance

3.5.1 Summary condition

In general, measurable human disturbance of streams at Glacier is restricted to select front country locations and may only be an area of concern for the park where it creates a meaningfully impacted ecological response. During our survey, 22 stream sites (out of 49) had negligible human disturbance (HDI = 0; Human Disturbance Index). Of the other 27 sites, most (21) had minor or moderate human disturbance. Table 7 presents the full summary condition table for human disturbance in Glacier.

3.5.2 Overview

We begin the presentation of our results and their discussion with estimates of overall or general human disturbance to streams across the Glacier landscape in 2007–2009. We present these results early in this report in large part because many of the successive sections use disturbance as a key gradient or covariate by which a stream response is interpreted. We focus on a general HDI as it better captures cumulative or multiple types of disturbance potentially impacting streams in the park.

Estimating human disturbance is an important part of stream monitoring. Streams are highly sensitive to anthropogenic disturbances and there is a long history of research seeking to understand the effects of this so that resource management may be better focused on protecting and restoring stream condition. Documenting and interpreting the response of streams to human disturbance across time and space is a primary purpose of SEI monitoring.

Our estimate of human disturbance (HDI) to streams in Glacier has some important caveats. It is a general index, not intended to describe specific stressors, such as excess nutri-

Table 7. Summary condition table for human disturbance at Glacier National Park in 2007–2009. We structure the table by indicators of stream ecological integrity (SEI). We include a brief description of key results and symbolize the status and our confidence in these summaries. Key to the condition and confidence symbol: red color = non-reference condition/major disturbance, yellow color = intermediate condition/ moderate disturbance, dark green color = reference condition/minor disturbance, light green color = pristine reference condition/negligible disturbance, no color = unknown or indeterminate; upward arrow = condition is improving, sideways arrows = condition is unchanging, downward arrow = condition is deteriorating, no arrow = unknown trend; heavy border = high confidence, regular border = medium confidence, dashed border = low confidence. Table 5 offers a visual key. For a condensed version of these results, see the summary condition table in the Executive Summary.

Indicator	Condition description	Condition and confidence
Human Disturbance	One of the foundations of SEI monitoring is the estimation of human disturbance(s) that impact Glacier's streams and potentially degrade ecological integrity. We use a Human Disturbance Index (HDI) to quantify a suite of reach scale human stressors as well as catchment scale human stressors at each monitoring site. In 2007–2009 there was a strong gradient in human disturbance across streams in the park. Almost 60% of the streams in the park were in a negligible disturbance class, with no evidence of human disturbance at the reach scale and no roads intersecting the stream network in a site's catchment. Around 17 and 16% of the stream sites in the park were in minor and moderate human disturbance classes, respectively. These sites were often near minor front country facilities or less traveled road corridors. They often had some near-channel human land use. Finally, about 11% of streams in the park were in a major human disturbance class. These were located near primary visitor service facilities and/or paved and well-traveled road corridors. In the concluding sections of this report, we link human disturbance to biological response and show that the majority of the park's negligibly disturbed streams are in a reference condition, with high ecological integrity. We suggest that the majority of the park's streams are secure and that this is generally not an important area of concern for the park. Models of human disturbance confirmed the importance of roads and structures in elevating human disturbance. Several natural gradients, such as elevation and geographic location in the park, also covaried with human disturbance. We have high confidence in our assessment of human disturbance given acceptable signal in the data, an unbiased sample design, rigorous data collection, and quality assurance. *Our models showed that longer term and larger scale disturbances, such as minimum summertime stream water temperatures, also positively varied with human disturbance. This might be suggestive of potentially troublesome interactions between climate change driven increases in a key stream ecological attribute (water temperature) and levels of proximate human use in and near the park's streams.*	

ents or high stream water temperatures (Muhlfeld et al. 2011, 2016). We estimate many of these specific stressors and present these results in other sections of this report. However, for many of these specific measures, the cause for a high level in Glacier is often not anthropogenic – this kind of a stressor may be common in a wilderness national park like Glacier and must be interpreted with caution. Our HDI composites multiple kinds of disturbances and is relativized or scaled to the data used to estimate it. Thus while it is similar in its construction and in the patterns it reveals across the park to other estimates of human disturbance applied across broader scales (Stoddard et al. 2005; Suplee et al. 2005), our HDI results and assessments apply only to streams in Glacier. It is ultimately unknown whether a high disturbance site in Glacier would also be classified as a high disturbance site outside of the park. Our overall impression is that Glacier's streams are on the low stress end of the gradient in comparison to ecoregion sites, but this will require more research and a better understanding of natural disturbances, and the ecological response to them, in the park.

The data used to set assessment points for HDI come exclusively from SEI sites – our HDI is not available at our partners' ecoregional sites. This has the benefit of making the context for setting reference conditions specific to streams in the park. It has the risks of (at least a conceptual) circularity and a reduced sample size.Regardless, the most important assessment of ecological condition is not via HDI, rather it is the relationship between HDI and biological response (which we estimate via models presented in the bioassessment section of this report).

3.5.3 Human disturbance: detailed results and interpretation

3.5.3.1 Site-specific results

We first present estimates of human disturbance at the site scale. Note that these estimates may be different from those based on design-based (parkwide) inference as they do not include attributes of the design in their estimation and do represent unsampled streams from the target population of streams. Human disturbance to streams was highest in larger (higher order) streams (Table 8), although the dispersion in each stream order class and models we present below indicate that these are not significant differences. This may be a sample size effect, as most larger streams are in valley bottoms, often in front country areas of the park where historical and current human land use, such as visitor services, are concentrated. Interestingly, every stream order had at least one site in a major disturbance class.

Figure 17 shows the spatial distribution of HDI values across the park. In general, higher disturbance occurs on the boundaries of the park and along visitor services corridors (i.e., the Going to the Sun Road that bisects the park east to west). These areas typically have roads, buildings, and sanitation facilities, and are closer to several existing and abandoned point sources. Almost every backcountry wilderness stream had negligible disturbance. A few sites did have a low impact trail or backcountry campsite nearby, and these sites were classified as having minor disturbance.

3.5.3.2 Parkwide results

Next, we present design-based results that infer human disturbance to all streams in the park. Design-based inference uses a suite of algorithms to estimate population means and various estimates of the error in these means. Figure 18 gives the cumulative distribution of HDI across the population of streams in Glacier during 2007–2009. The cumulative value is given both as a proportion of the total resource and as estimates of total length of stream. An estimate of the error in the population scale inference is given by a 95% confidence interval around the cumulative value. Table 9 presents these estimates in the context of ecoregional and negligible assessment points (see above) and the proportion of stream length in each of the four classes defined by these. We also illustrate the proportion of stream length in each disturbance class with a pie chart embedded in Figure 18. While visually useful, the pie chart does not show the confidence interval around the proportion of stream in each class, as in the cumulative distribution, and should be used with caution.

The mean HDI was below 0.5, suggesting the observed human disturbance in most Glacier streams was well below an "average" (0.5 or 50%) expected value, given a normal distribution. The cumulative distribution does not even appear until near an HDI score of 0.6, reflecting the large percentage (around 60%, with a 40–74% confidence interval) of Glacier streams with negligible or zero human disturbance. About 17 and 16% of the streams in the park were in minor and moderate disturbance classes, respectively, with 95% confidence intervals around these estimates of around 16–19% and 11–18%. Finally a smaller percentage (about 11%, +/- 0 to 24%) of streams in the park were in a major disturbance class (note this is seen in the short and steep right tail of the cumulative distribution).

Signal : noise

S:N for HDI was derived across all 49 sites and the 97 visits to these sites from 2007 to 2009. The data behind the road–stream crossing density component within the HDI do not vary across revisits; regardless, we expect the data rarely vary over a span of three years anyway. We present the methods behind S:N in detail in Appendix D. HDI had an S:N ratio of 12.4 in 2007–2009. This indicates that HDI is likely to show a consistent response to its drivers (Stoddard et al. 2008) and distinguish among sites. In other words, most of the variance in HDI is across sites versus within sites across time, suggesting it is a statistically reliable metric.

Table 8. Summary of the Human Disturbance Index (HDI) at the site level in Glacier National Park in 2007–2009. Results are grouped by stream order. HDI ranges from 0 to 1, with increasing levels of disturbance. LCL/UCL are lower and upper 95% confidence intervals. Standard error is for the mean. Source data are the 49 best sample events in 2007–2009.

Stream order	Valid N	Mean HDI	LCL	UCL	Min	Max	Standard Deviation	Standard Error
1	4	0.23	0	0.93	0	0.89	0.44	0.22
2	5	0.19	0	0.67	0	0.88	0.39	0.17
3	16	0.13	0	0.25	0	0.76	0.24	0.06
4	13	0.11	0	0.27	0	0.94	0.26	0.07
5	7	0.52	0.20	0.85	0	1.00	0.35	0.13
6	4	0.32	0.06	0.57	0.15	0.51	0.16	0.08
All	49	0.21	0.12	0.30	0	1.00	0.31	0.04

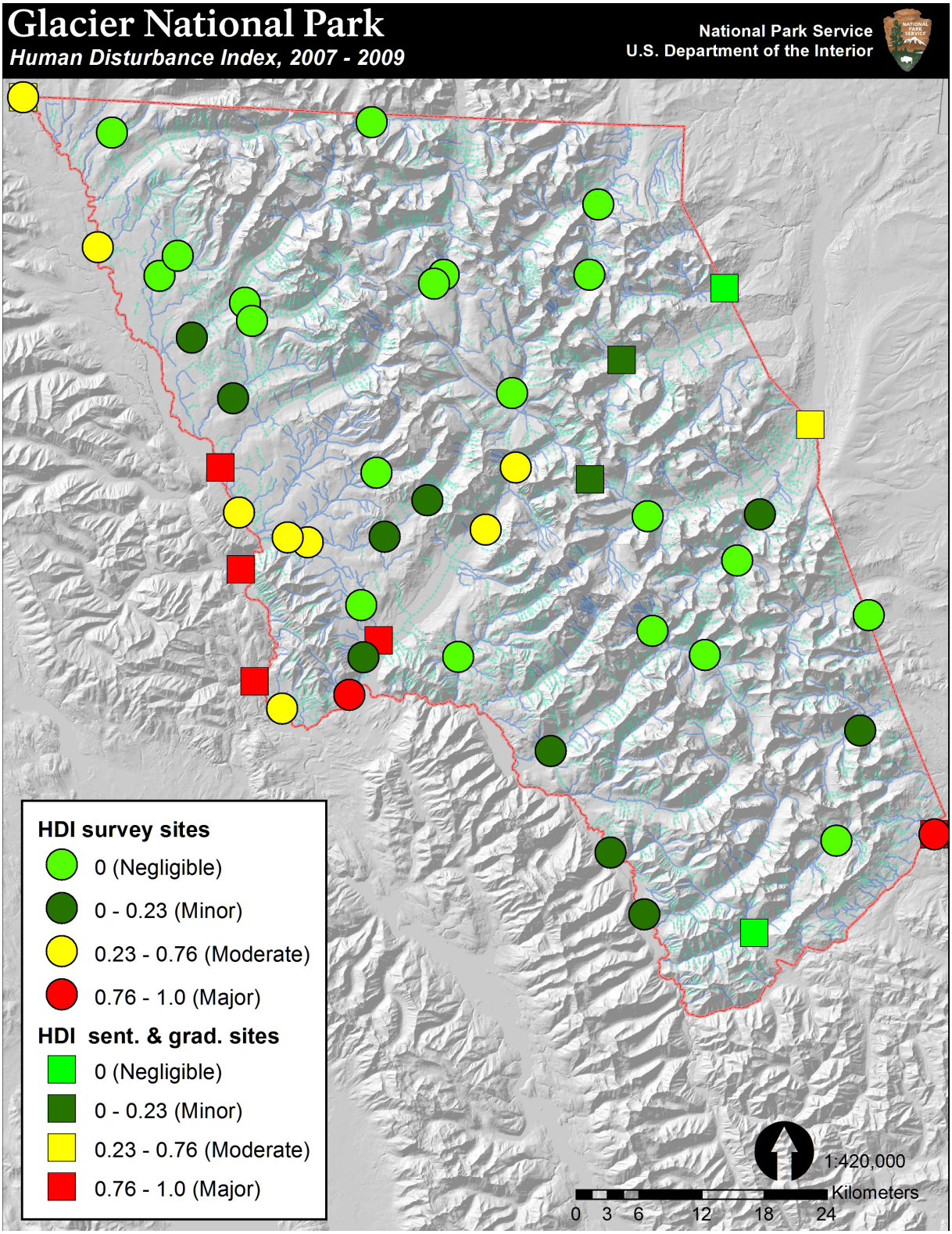


Figure 17. Map of Human Disturbance Index (HDI) at Stream Ecological Integrity survey sites and sentinel (sent.) and gradient (grad.) sites in Glacier National Park, 2007–2009. HDI ranges from 0 to 1 with increasing levels of disturbance. Colored disturbance classes are based on ecoregional assessment at the >95th percentile for major disturbance (red dots), and a <75th percentile for minor disturbance (dark green dots). A moderate disturbance class falls in between these values (yellow dots). For negligible disturbance we use HDI = 0 (light green dots). Background stream layer includes perennial (solid blue lines) and non-perennial reaches (dashed teal lines). See Appendix A for a complete list of site numbers and names.

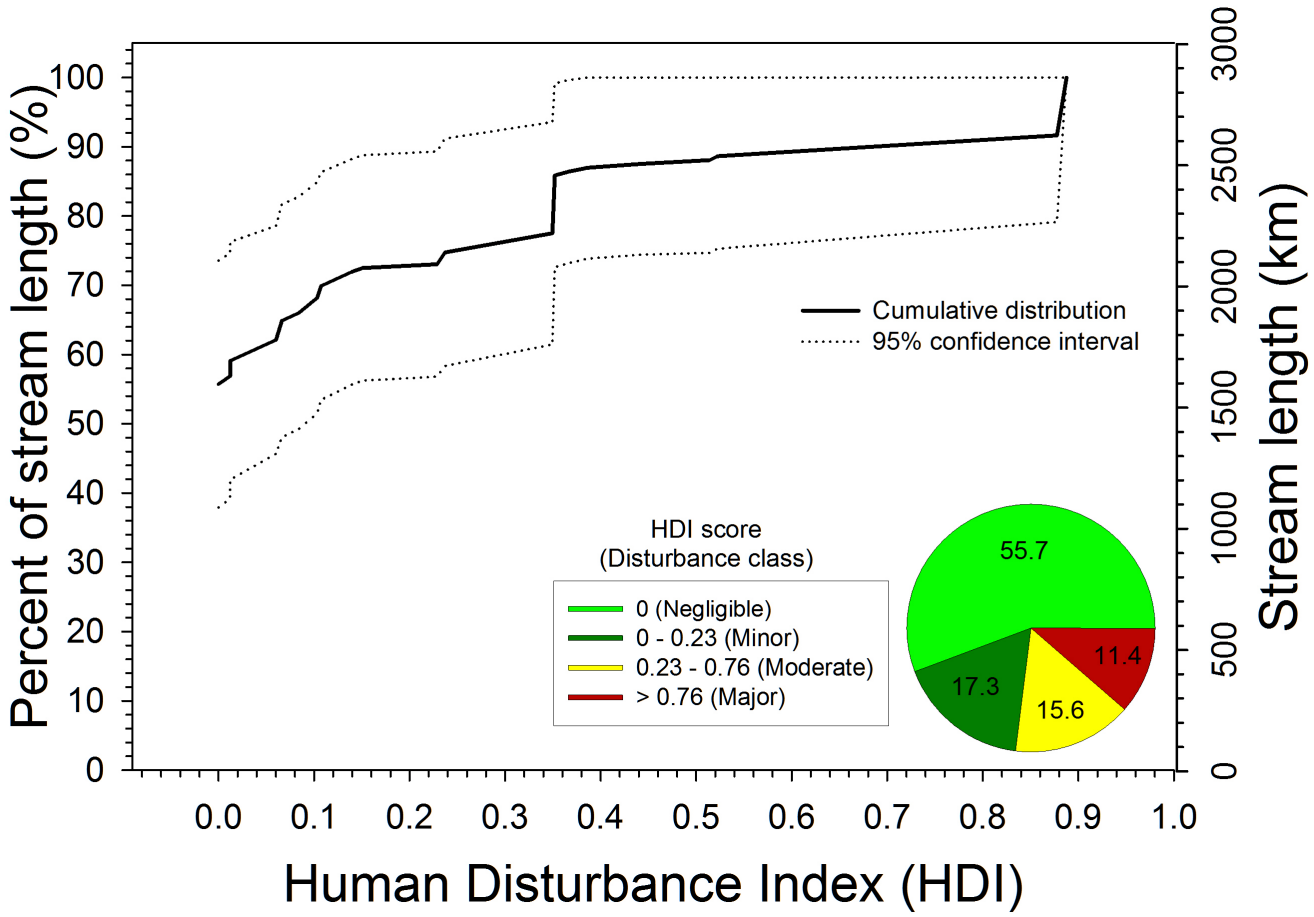


Figure 18. Cumulative distribution of the Human Disturbance Index (HDI) for the population of Glacier streams, 2007–2009. HDI ranges from 0 to 1 with increasing levels of disturbance. The left y-axis gives the percent of stream length in the park and the right y-axis shows the actual estimated length of stream. A 95% confidence interval (dotted lines) around the percent values (heavy line) is also shown. Assessment points are set at a zero value of HDI and derived from reference sites in the park and its surrounding ecoregions at the 95th (0.76) and 75th percentile (0.23). Pie chart shows the percentage and numeric values for the total length in each disturbance class as light green (negligible disturbance), dark green (minor disturbance), yellow (moderate disturbance), and red (major disturbance). Pie charts do not include a confidence interval for each estimate in these classes, so they should be used with caution.

Table 9. Summary statistics and application of assessment points to estimates of Human Disturbance Index (HDI) for the parkwide population of streams in Glacier National Park, 2007–2009.

						Assessment points			Proportion in disturbance class			
Metric	N	Mean HDI value	SE[1]	LCB[2]	UCB[2]	0	75th	95th	Negligible	Minor	Moderate	Major
HDI	40	0.17	0.06	0.05	0.29	0	0.23	0.76	55.7	17.3	15.6	11.4

Note : HDI ranges from 0 to 1 with increasing levels of disturbance. Baseline assessment points (minor, moderate, major) are set following EPA (2015) and Stoddard et al. (2008) from a distribution of MDC (Minimally Disturbed Condition) reference sites defined *a priori* in Glacier National Park following Suplee et al. (2005). We define a negligible assessment point as an HDI value of zero. Confidence intervals around each of the proportions in these disturbance classes are discussed on the following page.

[1] SE = standard error for the mean.

[2] LCB and UCB = lower and upper bounds on a 95% confidence interval around the population mean.

3.5.4 Exploratory model of human disturbance

Next, we present an exploratory model of HDI and select environmental variables. Models were initiated with 18 potential independent variables. We chose the initial independent variables based on statistical attributes (i.e., measures that had strong univariate correlation with HDI), those that might have the most utility for stream resource management in Glacier, and those that our collective experience suggested might assist in our interpretation of human disturbance to streams.

The final model of HDI included seven independent variables (Table 10). It was highly significant ($p < 7.472e-08$), with an adjusted r^2 of 0.63, indicating much of the variation in HDI was accounted for. Complete models are presented in Appendix F. We focus our interpretation here on select variables in the model that either had high relative importance, low p-values, and/or interesting relationships as drivers or covariates of HDI. We use conditional plots of partial residuals to visualize the model (Figure 19; Larsen and McCleary 1972; Breheny and Burchett 2013).

Our model of HDI included several interesting and potentially management relevant predictors or covariates of HDI.

First, with a relative importance of 42%, logged distance to road was negatively associated with HDI (sites closer to roads had higher HDI; note because of the log, a unit increase in HDI can occur with a small decrease in distance to road). This mirrors the well-documented negative effect of roads on aquatic systems (Forman and Alexander 1998; Spellerberg 1998; Trombulak and Frissell 2000; McBride and Booth 2005; Theobald 2005). While many factors impact where Glacier might place roads in the park, our results suggest that juxtaposition relative to streams should also be considered. Note that we included this variable with some concern, given the similar road–stream crossing density variable in the HDI index itself. We feel that distance to road is functionally distinct from road–stream crossing density. It is also more tangible and perhaps more readily subjected to management control. Nevertheless this should be considered when interpreting this pattern and viewed as a covariate with HDI not a direct predictor.

Next, the density of structures in a site's catchment, with a relative importance of 11%, was positively related to HDI. Sites with a higher density of structures had higher HDI (again because of the log, a unit increase in HDI can occur with a small increase in structure density). This pattern is driven by two potential outlier sites; however, if these are removed, the bivariate fit is actually much better and more markedly positive. As with roads this variable should be treated with caution given that the presence of structures was one of the human stressors quantified by crews at each site and included in the HDI. However here it accounts for structures not visible to crews, potentially at some distance from the stream site.

Table 10. Model of Glacier National Park Human Disturbance Index (HDI) in 2007–2009. Final model selected using Akaike Information Criterion (AIC) and expert opinion from 18 candidate variables. Relative importance (Rel. Imp %) is the total amount of explained variance for each variable expressed as a percentage. Watershed is treated as a factor and all estimates are relative to the Hudson Bay drainage; Relative importance value for watershed[1] is for all groups combined.

Model component	Estimate	SE	t	p	Rel. Imp. (%)
Intercept	1.583	0.367	4.317	0.000	–
Watershed—Middle Fork of the Flathead	-0.053	0.122	-0.436	0.665	–
Watershed—Missouri	0.094	0.149	0.634	0.530	–
Watershed—North Fork of the Flathead	0.168	0.142	1.182	0.244	–
Watershed—all groups combined	–	–	–	–	0.126[1]
Riparian buffered disturbance, index (log)	-1.408	0.973	-1.448	0.156	0.081
Distance (m) to nearest road (log)	-0.082	0.022	-3.631	0.001	0.424
Elevation (m)	-0.001	0.000	-2.631	0.012	0.168
% catchment burned since 1984 (log)	-0.049	0.031	-1.597	0.118	0.072
Min. catchment stream temperature (°C)	0.018	0.013	1.375	0.177	0.022
Structure density in catchment (log)	0.232	0.242	0.958	0.344	0.107

Note: SE = standard error of coefficient, t = t test value, p = probability of the t. Residual standard error: 0.18 on 39 degrees of freedom, Multiple R^2: 0.7013, Adjusted R^2: 0.63, F-statistic: 10.17 on 9 and 39 DF, p-value: 7.472e-08.

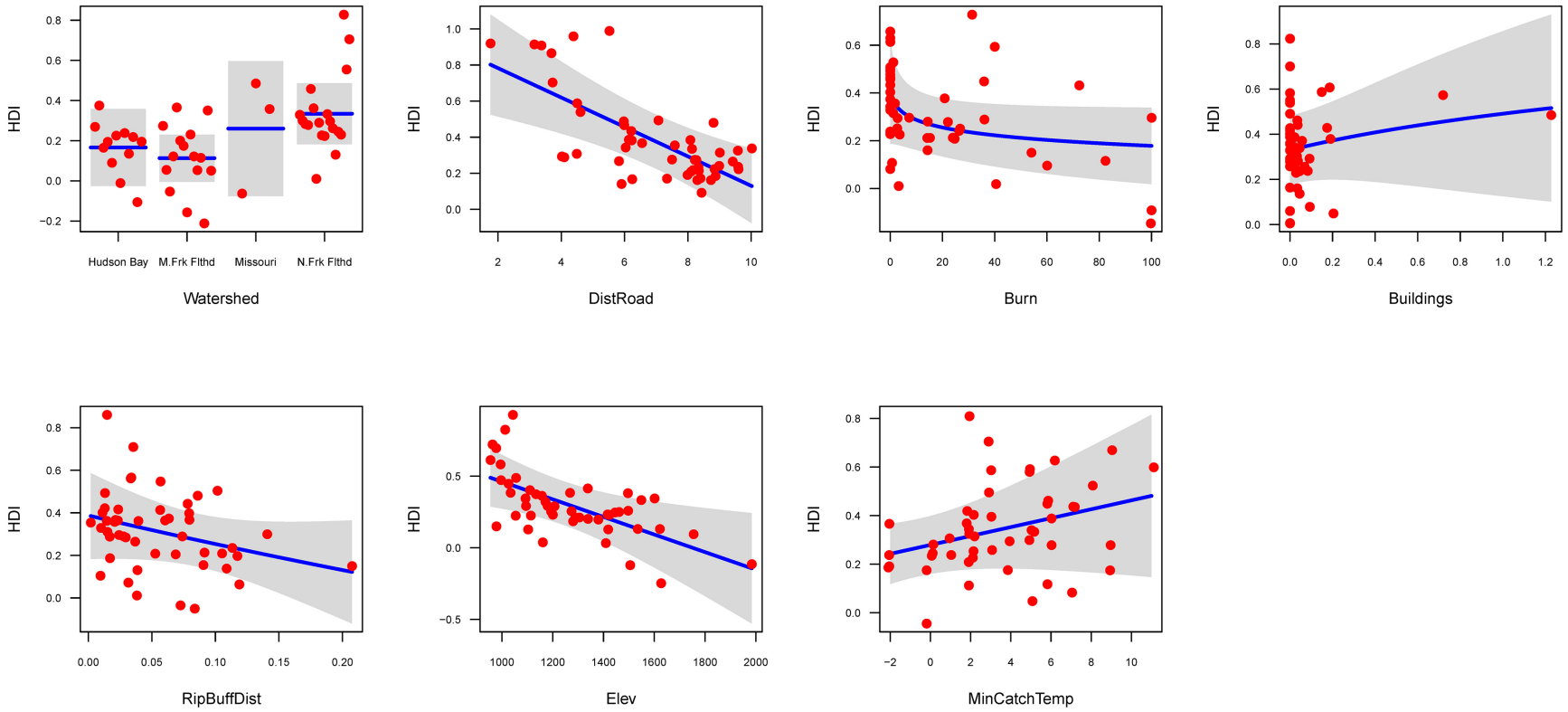


Figure 19. Partial residual plots of exploratory model of Glacier National Park Human Disturbance Index (HDI) in 2007–2009. Conditional partial residuals show the relationship between each unique predictor and HDI, with all other variables held constant at the median for numeric variables and most common level for factors. All variables are shown back transformed to their original scale as applicable. Plots of numeric predictors include a best fit line and 95% confidence bands around this fit. Box plots of factorial variables include the reference category first or on the leftmost side of the figure and the 95% confidence interval as the bounding box around the variable's median. Codes in figures are: HDI = Human Disturbance Index; Watershed = watershed membership; DistRoad = distance (m) to nearest road; Burn = % catchment burned since 1984; Buildings = structure density in catchment; RipBuffDist = riparian buffered disturbance index; Elev = elevation (m); MinCatchTemp = minimum catchment stream temperature (°C). See the full model results in Appendix F and Table 10.

Of the natural gradients, two, elevation and geographic location (by major watershed) in the park also covaried with human disturbance. HDI decreased with elevation, with a relative importance of 17%. Although we don't have a large number of high elevation sites, there was a strong effect of challenging accessibility and general remoteness on the degree of HDI at high elevation streams. Sites in the North Fork of the Flathead, and to a lesser degree, the Missouri watersheds, had elevated levels of HDI relative to sites in the Hudson Bay drainage (which had low levels of human disturbance). Overall watershed membership had a relative importance of about 13%.

Of the remaining three variables in the model (each with less than 9% importance), perhaps the most interesting was the minimum August stream water temperature in a site's catchment. This positively varied with human disturbance, meaning sites with higher minimum water temperatures had higher levels of disturbance. Because elevation is also in the model, this is not due to these sites being at lower elevation where it is usually warmer and there are more visitor services and other infrastructure. Rather it may be suggestive of potentially troublesome interactions between climate change driven increases in a key stream ecological attribute (i.e., water temperature; Giersch et al. 2011, 2016) and levels of proximate human use in and near the park's streams.

3.6 Water chemistry

3.6.1 Summary condition

Overall water chemistry in Glacier showed little cause for concern. Streams in a few areas (front country areas below lower Lake MacDonald Creek and Railroad Creek near East Glacier) showed some minor issues. Even in these few cases, without additional research, we cannot connect these water chemistry issues with a meaningful ecological response. Table 11 provides a summary condition of the major classes of water chemistry we monitored during our 2007–2009 survey.

3.6.2 Overview

Water chemistry parameters include important responses like nutrients and water temperature. Documenting the status and trends in such attributes is a fundamental part of monitoring streams and these attributes have been used for decades within multiple long-term programs. The physio-chemical environment of streams is the primary medium aquatic biota inhabit – its influence is akin to how the chemical composition and physical attributes of "air" affect terrestrial organisms. We treat water chemistry as one of the primary types of stressor included in SEI monitoring.

Interpretation of our water chemistry data has some important caveats, especially in a survey context. Most constituents are naturally variable seasonally or even daily. SEI survey methods may not effectively capture this temporal variance. We do sample survey sites at base flow, when most biota are stressed or at key points in their life cycles, and patterns in quality across sites provide a useful indicator of differential potential stress on biological condition. Moreover, by sampling at base flow, one of the more important points in the temporal dynamics of water chemistry, we hope to reduce the limitations of monitoring water chemistry via a large survey design approach.

Mills et al. (2011) present a detailed study of the North Fork of the Flathead that includes frequent samples of chemistry and integration with stream flow in the main stem and its tributaries that may account for spatial and temporal structure. While Mast (2007) makes some assumptions about inference to unsampled sites and comparisons across disparate sample designs, the report includes a comprehensive treatment of long-term patterns in water chemistry at select sites in the park. Our sentinel site approach (Schweiger et al. in preparation a), with replicate sampling across the hydrograph at select sites, replicates some of the approach in Mills et al. (2011) and thus does a better job at understanding temporal dynamics in water chemistry at select locations in the park.

Water chemistry, perhaps more than any other type of response, has the benefit of a spectrum of existing assessment points developed by Montana DEQ, EPA, and others for a variety of circumstances. In general we follow the hierarchy given in the assessment section 2.4.4.2, above, with specific details overviewed in Appendix D.

3.6.3 Water chemistry: detailed results and interpretation

The following sections present detailed water chemistry results and their interpretation. Our results are based on 2007–2009 survey site events (Table 12a–d). We include both population level and select site level results. Select models for stream water temperature and total phosphorous are relevant at the site scale. Results focused on patterns over time (change and trend) in select water chemistry parameters are presented in our sentinel site report (Schweiger et al. in preparation a).

3.6.3.1 *In Situ* field parameters

In situ water chemistry at SEI survey sites in 2007–2009 showed a fairly wide range, likely due to the high levels of

Table 11. Summary condition table for water chemistry at Glacier National Park in 2007–2009. We structure the table by indicators of stream ecological integrity (SEI). We include the types of assessment points used, a brief description of key results, and symbolize the status and our confidence in these summaries. Key to the condition and confidence symbol: red color = non-reference condition/major disturbance, yellow color = intermediate condition/ moderate disturbance, dark green color = reference condition/minor disturbance, light green color = pristine reference condition/negligible disturbance, no color = unknown or indeterminate; upward arrow = condition is improving, sideways arrows = condition is unchanging, downward arrow = condition is deteriorating, no arrow = unknown trend; heavy border = high confidence, regular border = medium confidence, dashed border = low confidence. Table 5 offers a visual key. For a condensed version of these results, see the summary condition table in the Executive Summary.

Indicator	Condition description	Condition and confidence
Overall water chemistry	Overall water chemistry in Glacier showed little cause for concern. Streams in a few areas (front country below lower Lake MacDonald Creek and Railroad Creek near East Glacier) showed some minor water chemistry issues. Even with these few cases, without additional research, we cannot connect these water chemistry issues with a meaningful ecological response. Overall we have medium to high confidence in our assessment for water chemistry. There is acceptable signal in most parameters, and several relevant assessment points (criteria, ecological thresholds, and ecoregional based values) for many responses. However, measuring water chemistry appropriately often requires repeated or seasonal samples. We are confident that our results are useful baselines for understanding changes over time, given the high quality design, data, and modeling we employ.	
Core *in situ* parameters	Water chemistry parameters analyzed *in situ* include dissolved oxygen, pH, specific conductance, and water temperature sampled with probes. These parameters reflect short term processes important in many stream processes. In situ water chemistry at SEI survey sites in 2007–2009 showed a fairly wide range, likely due to the high levels of diel and seasonal variation. Overall, in situ parameters in Glacier from 2007–2009 do not suggest high levels of disturbance or problems in the park's streams. A small percentage of the park's streams may experience dissolved oxygen levels below levels required for young salmonids in the heat of the summer, but we expect these lower levels are short term and largely caused by natural patterns in canopy cover, water depth, etc. (note we do not have specific data that connect low oxygen levels to problems in the park's fisheries). There are no relevant assessment points for pH. However, overall there is no evidence that pH in the park was not "natural" (i.e., it is not a source of stress). pH is driven by levels of the dominant anion in the park's streams and weathering of the sedimentary rocks in Glacier. Given an expected linear response between increasing specific conductance and human disturbance in Glacier streams, we applied ecoregional assessment points to put specific conductance in the park in context. These suggest that most of the streams in Glacier were as dilute (low conductance) as reference sites in the surrounding ecoregions. However, more work, especially repeated sampling, is needed to fully interpret these results. Finally, while there are no relevant assessment points for our survey data, stream water temperature matched general expectations for base flow midday later summer instantaneous values in Glacier. Patterns in stream water temperature across our monitoring sites were complex and will require continued research. We have medium confidence in our assessment given the higher levels of temporal variation and a lack of appropriate assessment points for some parameters. However, we are confident that our results are useful baselines for understanding changes over time, given the high quality design, data, and modeling we employ. *Note that because of the connections we and other collaborators have seen between stream water temperature, climate change, and ecological response, we have given this class of responses an Intermediate condition, or moderate disturbance, designation. Water temperature is very important in streams and is susceptible to climate change. Therefore this is something to watch carefully into the future.*	

Table 11 (continued**).** Summary condition table for water chemistry at Glacier National Park in 2007–2009. We structure the table by indicators of stream ecological integrity (SEI). We include the types of assessment points used, a brief description of key results, and symbolize the status and our confidence in these summaries. Key to the condition and confidence symbol: red color = non-reference condition/major disturbance, yellow color = intermediate condition/ moderate disturbance, dark green color = reference condition/minor disturbance, light green color = pristine reference condition/negligible disturbance, no color = unknown or indeterminate; upward arrow = condition is improving, sideways arrows = condition is unchanging, downward arrow = condition is deteriorating, no arrow = unknown trend; heavy border = high confidence, regular border = medium confidence, dashed border = low confidence. Table 5 offers a visual key. For a condensed version of these results, see the summary condition table in the Executive Summary.

Indicator	Condition description	Condition and confidence
Major ions and suspended sediment	We measured several major ions at our sites across the park. Most variation in these responses in 2007–2009 was driven by reactions with naturally occurring surficial geology, and there is little regulatory context for these responses as sampled in our survey. Natural concentrations of major ions are important because they protect or buffer against rapid pH changes, which can be harmful to aquatic life. Overall, there was little evidence for problems with most major ions in the park's streams. However, sulfate, chloride and alkalinity can be useful indicators of human disturbance. Elevated levels have been linked to increased human use of streams and their watersheds (although this is in landscapes with more human disturbance than in Glacier). Relative to ecoregional reference sites, from 3 to 4.5% of Glacier's streams had levels of these three parameters and fell within a major stress class. The majority of the park's streams had concentrations on par with reference sites in surrounding ecoregions. Most waters were well buffered (low alkalinity), likely reflecting longer hydrologic flow paths and greater opportunity for rock–water interactions. Both sulfate and chloride levels have decreased nationwide, likely due to implementation of the Clean Air and Clean Water Acts. Nevertheless, any changes in land use in and around the park or shifts in the anthropogenic contribution to deposition might elevate chloride or sulfate. Our ecoregional assessment points serve as useful baseline values for future comparison should this occur. Sediment (total suspended sediment; TSS) can have a direct impact on stream biota and can be associated with elevated levels of nutrients and metals. Most Glacier streams had low TSS and were as sediment free as the best sites in the surrounding ecoregions. However, select sites, especially on larger rivers, such as the North Fork of the Flathead, had some excess total suspended sediment and associated bed sediments. These are likely mostly from natural sources, but given some development in the North Fork basin, this should be watched carefully. While more work is needed to better understand these patterns, it is likely that they have a relatively small localized effect on stream condition. We have high confidence in our assessment for these parameters given acceptable signal in the data and appropriate assessment points for several parameters. We are also more confident that our results are useful baselines for understanding changes over time, given the high quality design, data, and modeling we employ.	

Table 11 (continued**).** Summary condition table for water chemistry at Glacier National Park in 2007–2009. We structure the table by indicators of stream ecological integrity (SEI). We include the types of assessment points used, a brief description of key results, and symbolize the status and our confidence in these summaries. Key to the condition and confidence symbol: red color = non-reference condition/major disturbance, yellow color = intermediate condition/ moderate disturbance, dark green color = reference condition/minor disturbance, light green color = pristine reference condition/negligible disturbance, no color = unknown or indeterminate; upward arrow = condition is improving, sideways arrows = condition is unchanging, downward arrow = condition is deteriorating, no arrow = unknown trend; heavy border = high confidence, regular border = medium confidence, dashed border = low confidence. Table 5 offers a visual key. For a condensed version of these results, see the summary condition table in the Executive Summary.

Indicator	Condition description	Condition and confidence
Nutrients	We measured multiple nutrients (nitrogen, phosphorous, and carbon) at our sites across the park. The concentration of these nutrients are important in multiple aspects of stream ecology, and any biological response to excessive nutrient loading is central to the interpretation of a stream's ecological condition. Montana DEQ provides a rigorous approach to the assessment of total nitrogen and phosphorous and we apply an approximation of this methodology. Overall, there were few clearly human caused nutrient issues in the park's streams during this time period. A common way to interpret nutrient concentration in aquatic systems is the ratio of nitrogen to phosphorous. A ratio below 16 generally indicates possible nitrogen limitation. Ratios in Glacier are, on average, higher than 16, suggesting phosphorous was often a more limiting nutrient in the park's streams. This matches our observation that Glacier streams are oligotrophic, in general, with little to no eutrophication. A small (12–13%) percentage of the park's streams had high (relative to Montana DEQ ecoregion specific criteria) nutrient concentrations in late summer, yet we expect this is mostly due to natural sources (i.e., nutrient rich alluvial floodplain groundwater upwelling zones or wetlands). Our model of total phosphorous indicated that the most important predictors of concentrations were nitrogen and sediment concentrations (both of which had largely natural sources). However a few streams in the park may have impacts from localized human uses, including septic tank effluent (Fish Creek near Lake McDonald) and road runoff (especially streams on the park's boundary like Railroad Creek). There is little evidence, however, for any pervasive impact from nutrients on the base of the aquatic food chain (diatoms) or on macroinvertebrate communities that support important fish and other species in the park. Oligotrophic waters, like in Glacier, are inherently sensitive to even low inputs of nutrients. Because recent evidence from other research suggests phosphorous is increasing nationwide, even in undisturbed watersheds such as in Glacier, we do rate nutrients as a more concerning issue that will require careful future monitoring. We have medium confidence in our assessment for these parameters given smaller than ideal sample sizes of nutrient concentrations that would capture temporal and seasonal dynamics. More complex temporal patterns in nutrients are presented in the SEI sentinel report (in preparation). We are more confident that our results will be useful baselines for understanding changes over time, given the high quality design, data, and modeling we employ. *Of special note, exploratory models suggested that hydrology (i.e., stream flow) was important in influencing nutrient levels. Because hydrologic regime in streams is connected to climate change, this could have important indirect and complex implications and is something to watch carefully into the future.*	
Metals	We analyzed samples for concentrations of 12 metals in 2007–2009. Excess metals are an important source of toxicity in many streams worldwide. However, overall, metals in the streams of Glacier were of little concern. Very few sampling events had detectable concentrations and no median values were above any assessment point. Low metal concentrations are not unexpected given the neutral to basic pH of most water in the park and the lack of mining or urban sources of metals. However, it is primarily the dissolved form of metals that causes aquatic toxicity and is more relevant to long-term ecological monitoring. If funding is available, future work should include lab analyses of dissolved metals, even though our analysis of metals concentrations did not indicate cause for concern. There is usually also a strong seasonal effect in the concentrations of metals, with peaks during runoff reflecting greater sediment transport. We report on temporal patterns in metals in the SEI sentinel report (in preparation). We have high confidence in our assessment for metals. We are confident that our results will be useful baselines for understanding changes over time, given the high quality design, data, and modeling we employ.	

Table 12a. Summary of *in situ* field properties from 2007 –2009 water chemistry monitoring at the streams of Glacier National Park.

Constituent	N (est. N)[a]	Mean value from survey sites (all sites)	Park scale median	Max. value from survey sites (all sites)	LCL	UCL	Assessment points		Assess-ment point type	% of park streams in stressor class			Signal to Noise ratio (S:N)
							Major	Minor		Major	Moderate	Minor	
Dissolved oxygen (mg/l)	36[b]	7.5	9.3	15.2	9	10.04	<8.0[1a]	<4.0[1b]	THR	14	–	100	0.10
pH (standard units)	37[b]	6.9	8.2	9.5	7.89	8.25	–	–	–	–	–	–	2.69
Specific conductance (µS/cm)	37[b]	28(25)	143.7	462.3	112.25	212.84	>284[2a]	<163[2b]	ERG	5.1	36.4	58.5	16.38
Temperature, water (°C)	37[b]	5.9	9.4	16.9	8.69	12.33	–	–	–	–	–	–	0.78

Notes: Median and confidence intervals derived from survey-design-based estimation methods. Minimum and maximum values are at the site scale and (if meaningfully different) given for survey only sites and all sites (in parentheses). Codes for assessment point types are: THR = ecological threshold; ERG = ecoregional. Numbered table notes provide additional details on each type of assessment point. We assume for all parameters except dissolved oxygen that concentrations increase with a decrease in ecological condition. For ERG assessment points, we use the >95th percentile for major disturbance. We use a <75th percentile for minor disturbances. A moderate disturbance class falls in between these values. The percentage of Glacier National Park streams in major/moderate/minor stressor classes was derived by comparing design-based results to assessment points. Note that where there is only one assessment point there is no moderate class and we therefore lump moderate and minor categories. Some percentages are approximate as assessment points often fell between two values in the cumulative distribution and had therefore be interpolated. S:N was derived across all 49 sites and the 97 visits to these sites from 2007 to 2009. Problematic S:N values are below 1.0. mg/l = milligrams per liter, µS/cm = microsiemens/centimeter.

[a] Values for raw valued sample size are total N with the number of estimated values from Regression of Order (ROS) models in parentheses.

[b] The sample size (N) for in situ field properties is the number of unique sample events - the number of discrete data values within each event ranged from 7 to >3400.

[1a/b] Freshwater Aquatic Life Standards for dissolved oxygen are cold water one day minima for (a) early life stages and (b) other life stages. They are instantaneous water column concentrations to be achieved at all times (Montana DEQ 2002, 2012b, 2017).

[2a/b] Ecoregional assessment points generated from reference sites in the Northern and Canadian Rockies ecoregion, including Glacier (Stoddard et al. 2005, 2006) at the (a) >95th percentile values for major disturbance, and (b) <75th percentile values for minor disturbance. The moderate disturbance class falls in-between these values, or from the 95th to the 75th percentile.

Table 12b. Summary of inorganic ions and sediment from 2007–2009 water chemistry monitoring at the streams of Glacier National Park.

Constituent	N (est. N)[a]	Mean value from survey sites (all sites)	Park scale median	Max. value from survey sites (all sites)	LCL	UCL	Assessment points			Assess-ment point type	% of park streams in stressor class			Signal to Noise ratio (S:N)
							Major	Minor	Trigger		Major	Moderate	Minor	
Alkalinity, total (mg/l as CaCO3)	40	12.8 (-0.45)	61.5	248.7 (-154.8)	51.20	100.22	>144.2[2a]	<99.5[2b]	–	ERG	4.2	27.8	68	2.92
Calcium, total (mg/l)[b]	34	3.5	16.1	70	14.97	23.59	–	–	–	–	–	–	–	8.68
Chloride, diss. (mg/l)[c]	40(17)	0.009 (0.009)	0.28	3.8	0.11	0.33	>0.77[2a]	<0.32[2b]	–	ERG	3	30.6	66.4	1.14
Fluoride, diss. (mg/l)[d, e]	–	–	–	–	–	–	>4[3]	–	T:0.005[4]	CRT	–	–	–	–
Magnesium, diss. (mg/l) [b]	36	0.7	5.4	20.9	4.14	7.21	–	–	–	–	–	–	–	7.34
Potassium, total (mg/l)[b, c]	34(31)	0.001	0.019	0.059(0.98)	–	–	–	–	–	–	–	–	–	–
Silica, diss. (mg/l as SiO2)	40	1.1 (0.87)	4.1	11.4	2.86	4.98	–	–	–	–	–	–	–	4.41
Sodium, total (mg/l)[b, c]	34(12)	0.03	0.6	9.98	0.15	1.1	–	–	–	–	–	–	–	0.42
Sulfate, diss. (mg of S04/l)	40	0.27	2.8	10.89	2.04	3.19	>8.6[2a]	<4.6[2b]	–	ERG	4.5	18.5	77	3.29
Total suspended sediments (mg/l)[c]	40(15)	0.01 (-0.1)	1.2	26.0 (-63.8)	0.2	1.62	>6.7[2a]	<1.7[2b]	–	ERG	12.2	17.6	70.2	0.47

Notes: Median and confidence intervals derived from survey-design-based estimation methods. Minimum and maximum values are at the site scale and (if meaningfully different) given for survey only sites and all sites (in parentheses). Codes for assessment point types are: ERG = ecoregional; CRT = regulatory criterion; T = the Montana DEQ (2012b, 2017) trigger threshold for allowed changes in outstanding resource waters (see text). Numbered table notes provide additional details on each type of assessment point. We assume for all parameters that concentrations increase with a decrease in ecological condition. For ERG assessment points, we use the >95th percentile for major disturbance. We use a <75th percentile for minor disturbances. A moderate disturbance class falls in between these values. The percentage of Glacier National Park streams in major/moderate/minor stressor classes was derived by comparing design-based results to assessment points. Note that where there is only one assessment point there is no moderate class and we therefore lump moderate and minor categories. Some percentages are approximate as assessment points often fell between two values in the cumulative distribution and had therefore be interpolated. S:N was derived across all 49 sites and the 97 visits to these sites from 2007 to 2009. Problematic S:N values are below 1.0. mg/l = milligrams per liter.

[a] Values for raw valued sample size are total N with the number of estimated values from Regression of Order (ROS) models in parentheses.

[b] Total fraction was sampled and analyzed in 2007-08; switched to dissolved in 2009 as specified by Montana DEQ (2012b). However, given near or below detection values we combined total and dissolved values and interpret using assessment points for dissolved fractions.

[c] Value is or contains predicted results from ROS model; use with caution.

[d] >80% of results at method detection limit(s); results tenuous; use with extreme caution.

[e] Nitrite, nitrate and fluoride were not included in 2007 and 2008 sample analyses and there is insufficient N from 2009 for design based analysis.

[1a/b] Freshwater Aquatic Life Standards for dissolved oxygen are cold water one day minima for (a) early life stages and (b) other life stages. They are instantaneous water column concentrations to be achieved at all times (Montana DEQ 2002, 2012b, 2017).

[2a/b] Ecoregional assessment points generated from reference sites in the Northern and Canadian Rockies ecoregion, including Glacier (Stoddard et al. 2005, 2006) at the (a) >95th percentile values for major disturbance, and (b) <75th percentile values for minor disturbance. The moderate disturbance class falls in-between these values, or from the 95th to the 75th percentile.

Table 12c. Summary of nutrients in water or periphyton from 2007 –2009 water chemistry monitoring at the streams of Glacier National Park.

Constituent	N (est. N)[a]	Mean value from survey sites (all sites)	Park scale median	Max. value from survey sites (all sites)	LCL	UCL	Assessment points			Assess-ment point type	% of park streams in stressor class			Signal to Noise ratio (S:N)
							Major	Minor	Trigger		Major	Moderate	Minor	
Ammonia, diss. (mg/l as N)[b]	40(4)	0.002 (0.001)	0.008	0.02	0.005	0.009	–	–	T: 0.01[1]	–	–	–	–	0.21
Nitrite+Nitrate, diss. (mg/l as N)[b]	40(3)	0.0006 (0.001)	0.04	0.32	0.009	0.099	–	–	T: 0.01[1]	–	–	–	–	4.12
Nitrite, diss. (mg/l as N)[c]	–	–	–	–	–	–	–	–	T:0.004[1]	–	–	–	–	–
Nitrate, diss. (mg/l as N)[c]	–	–	–	–	–	–	–	–	T: 0.01[1]	–	–	–	–	–
Nitrogen, total (mg/l as N)	40	0.03 (0.02)	0.15	0.58	0.10	0.18	>0.325[2,3]	–	T: 0.01[1]	CRT	13	–	87	2.22
Orthophos., diss. (mg/l as P)[b]	40(2)	0.0001	0.001	0.02	0.0009	0.001	–	–	T:0.001[1]	–	–	–	–	2.59
Phosphorous, total (mg/l as P)[b]	40(4)	0.0009 (-0.001)	0.01	0.059	0	0.02	>0.025[2,3]	–	–	CRT	12	–	88	1.5

Notes: Median and confidence intervals derived from survey-design-based estimation methods. Minimum and maximum values are at the site scale and (if meaningfully different) given for survey only sites and all sites (in parentheses). Codes for assessment point types are: CRT = regulatory criterion; T = the Montana DEQ (2012b, 2017) trigger threshold for allowed changes in outstanding resource waters (see text). Numbered table notes provide additional details on each type of assessment point. We assume for all parameters that concentrations increase with a decrease in ecological condition. For ERG assessment points, we use the >95th percentile for major disturbance. We use a <75th percentile for minor disturbances. A moderate disturbance class falls in between these values. The percentage of Glacier National Park streams in major/moderate/minor stressor classes was derived by comparing design-based results to assessment points. Note that where there is only one assessment point there is no moderate class and we therefore lump moderate and minor categories. Some percentages are approximate as assessment points often fell between two values in the cumulative distribution and had therefore be interpolated. S:N was derived across all 49 sites and the 97 visits to these sites from 2007 to 2009. Problematic S:N values are below 1.0. mg/l = milligrams per liter, mg/m^2 = milligrams per meter squared.

[a] Values for raw valued sample size are total N with the number of estimated values from Regression of Order (ROS) models in parentheses.

[b] Value is or contains predicted results from ROS model; use with caution.[e] Nitrite, nitrate and fluoride were not included in 2007 and 2008 sample analyses and there is insufficient N from 2009 for design based analysis.

[c] Nitrite, nitrate and fluoride were not included in 2007 and 2008 sample analyses and there is insufficient N from 2009 for design based analysis.

[d] Zero value for chlorophyll a is due to mistake in lab processing in 2007.

[1] Trigger ("T") is the value for a change in concentration (usually an increase) not to be exceeded to preserve outstanding resource waters, as defined by Montana DEQ (2012b, 2017).

[2] State of Montana chronic aquatic life standards (Montana DEQ 2012b, 2017).

[3] Total nitrogen and phosphorous are for summer time base flow in the Canadian Rockies Ecoregion (Suplee and Sada de Suplee 2011; Suplee and Watson 2013).

[4] Nutrient assessment support criteria are for summer time base flow in the Canadian Rockies Ecoregion (Suplee and Sada de Suplee 2011; Suplee and Watson 2013).

Table 12c (continued). Summary of nutrients in water or periphyton from 2007 –2009 water chemistry monitoring at the streams of Glacier National Park.

Constituent	N (est. N)[a]	Mean value from survey sites (all sites)	Park scale median	Max. value from survey sites (all sites)	LCL	UCL	Assessment points			Assess-ment point type	% of park streams in stressor class			Signal to Noise ratio (S:N)
							Major	Minor	Trigger		Major	Moderate	Minor	
Carbon, org., diss. (mg/l as C)	38	0.17	1.1	7.98	0.97	2.91	–	–	–	–	–	–	–	3.03
Carbon, org., total (mg/l as C)[b]	38(2)	0.22	1.2	16.04	0.82	1.78	–	–	–	–	–	–	–	3.21
Chlorophyll a (mg/m^2)	40	0[d]	5.9	40.38	4.11	10.31	>125[4]	–	–	CRT	0	–	100	0.09
Ash free dry mass (mg/m^2)	40	0.89	6.8	38.64	5.03	13.98	>35[4]	–	–	CRT	10	–	90	0.56
Integrated Montana DEQ Nutrient Assess-ment – Rocky Mountain Network approxima-tion: Network Tier I - II evaluation	40	Pass (0)	–	Fail (1)	–		>43	–	–	CRT	8.3	91.7	–	–

Notes: Median and confidence intervals derived from survey-design-based estimation methods. Minimum and maximum values are at the site scale and (if meaningfully different) given for survey only sites and all sites (in parentheses). Codes for assessment point types are: CRT = regulatory criterion; T = the Montana DEQ (2012b, 2017) trigger threshold for allowed changes in outstanding resource waters (see text). Numbered table notes provide additional details on each type of assessment point. We assume for all parameters that concentrations increase with a decrease in ecological condition. For ERG assessment points, we use the >95th percentile for major disturbance. We use a <75th percentile for minor disturbances. A moderate disturbance class falls in between these values. The percentage of Glacier National Park streams in major/moderate/minor stressor classes was derived by comparing design-based results to assessment points. Note that where there is only one assessment point there is no moderate class and we therefore lump moderate and minor categories. Some percentages are approximate as assessment points often fell between two values in the cumulative distribution and had therefore be interpolated. S:N was derived across all 49 sites and the 97 visits to these sites from 2007 to 2009. Problematic S:N values are below 1.0. mg/l = milligrams per liter, mg/m^2 = milligrams per meter squared.

[a] Values for raw valued sample size are total N with the number of estimated values from Regression of Order (ROS) models in parentheses.

[b] Value is or contains predicted results from ROS model; use with caution.[e] Nitrite, nitrate and fluoride were not included in 2007 and 2008 sample analyses and there is insufficient N from 2009 for design based analysis.

[c] Nitrite, nitrate and fluoride were not included in 2007 and 2008 sample analyses and there is insufficient N from 2009 for design based analysis.

[d] Zero value for chlorophyll a is due to mistake in lab processing in 2007.

[1] Trigger ("T") is the value for a change in concentration (usually an increase) not to be exceeded to preserve outstanding resource waters, as defined by Montana DEQ (2012b, 2017).

[2] State of Montana chronic aquatic life standards (Montana DEQ 2012b, 2017).

[3] Total nitrogen and phosphorous are for summer time base flow in the Canadian Rockies Ecoregion (Suplee and Sada de Suplee 2011; Suplee and Watson 2013).

[4] Nutrient assessment support criteria are for summer time base flow in the Canadian Rockies Ecoregion (Suplee and Sada de Suplee 2011; Suplee and Watson 2013).

Table 12d. Summary of metals (trace elements) in water from 2007 –2009 water chemistry monitoring at the streams of Glacier National Park.

Constituent	N (est. N)[a]	Mean value from survey sites (all sites)	Park scale median	Max. value from survey sites (all sites)	LCL	UCL	Assessment points			Assessment point type	% of park streams in stressor class			Signal to Noise ratio (S:N)
							Major	Minor	Trigger		Major	Moderate	Minor	
Aluminum, diss. (µg/l)[b]	36(34)	–	–	–	–	–	>87[1]	–	T: 30[2]	CRT	–	–	–	–
Arsenic, total (µg/l)[c]	36(36)	–	–	–	–	–	>150[1]	–	T: 2[2]	CRT	–	–	–	–
Barium, total (µg/l)	36	10	49.6	200	38.71	74.44	–	–	–	–	–	–	–	6.45
Beryllium, total (µg/l)[c]	36(36)	–	–	–	–	–	–	–	–	–	–	–	–	–
Cadmium, total (µg/l)[c]	36(36)	–	–	–	–	–	>538.3[1,3]	–	T: 0.1[2]	CRT	–	–	–	–
Chromium, total (µg/l)[c]	36(36)	–	–	–	–	–	>58106.3[1,3]	–	T: 1[2]	CRT	–	–	–	–
Copper, total (µg/l)[c]	36(36)	–	–	–	–	–	>6183.4[1,3]	–	T: 0.5[2]	CRT	–	–	–	–
Iron, total (µg/l)[b]	35(31)	0.26	14.5	2410	5.37	24.52	>1000[1]	–	T: 0.1[2]	CRT	~2	99		–
Lead, total (µg/l)[c]	36(36)	–	–	–	–	–	>1724.1[1,3]	–	–	CRT	–	–	–	–
Manganese, total (µg/l)[d]	28(10)	0.02	0.88	674	0.29	2.52	–	–	–	–	–	–	–	0.14
Selenium, total (µg/l)[c]	36(36)	–	–	–	–	–	>5[1]	–	T: 0.6[2]	CRT	–	–	–	–
Zinc, total (µg/l)[b]	36(31)	0.005	0.05	27	0.02	0.10	>79693.1 [1,3]	–	T: 5[2]	CRT	0	–	100	–

Notes: Median and confidence intervals derived from survey-design-based estimation methods. Minimum and maximum values are at the site scale and (if meaningfully different) given for survey only sites and all sites (in parentheses). Codes for assessment point types are: CRT = regulatory criterion; T = the Montana DEQ (2012b, 2017) trigger threshold for allowed changes in outstanding resource waters (see text). Numbered table notes provide additional details on each type of assessment point. We assume for all parameters that concentrations increase with a decrease in ecological condition. For ERG assessment points, we use the >95th percentile for major disturbance. We use a <75th percentile for minor disturbances. A moderate disturbance class falls in between these values. The percentage of Glacier National Park streams in major/moderate/minor stressor classes was derived by comparing design-based results to assessment points. Note that where there is only one assessment point there is no moderate class and we therefore lump moderate and minor categories. Some percentages are approximate as assessment points often fell between two values in the cumulative distribution and had therefore be interpolated. S:N was derived across all 49 sites and the 97 visits to these sites from 2007 to 2009. Problematic S:N values are below 1.0. µg/l = micrograms per liter.

[a] Values for raw valued sample size are total N with the number of estimated values from Regression of Order (ROS) models in parentheses.

[b] >80% of results at method detection limit(s); results tenuous; use with extreme caution.

[c] All results at method detection limit(s); no ROS model possible and insufficient N for analysis.

[d] Value is or contains predicted results from ROS model; use with caution.

[1] State of Montana chronic aquatic life standards (Montana DEQ 2012b, 2017).

[2] Trigger ("T") is the value for a change in concentration (usually an increase) not to be exceeded to preserve outstanding resource waters, as defined by Montana DEQ (2012b, 2017).

[3] Values are derived from the State of Montana chronic aquatic life standards for a total fraction using formulas from EPA (2009) and a median hardness of 186 mg/l as $CaCO_3$ (Montana DEQ 2012b)

diel and seasonal variation. Interpreting survey based results for these responses is even more problematic than other water chemistry parameters given this variability. However, overall, most *in situ* results from Glacier in 2007–2009 do not suggest high levels of disturbance or systemic problems in the park's streams (Table 12a).

Dissolved oxygen

The State of Montana (Montana DEQ 2002) has established a minimum instantaneous dissolved-oxygen (DO) concentration of 8.0 mg/l for early life stages of fish and 4 mg/l for other life stages in class A-1 and Outstanding Resource Water (ORW) streams, such as in Glacier. We treat these as meaningful ecological thresholds in our assessment, and even though DO is a temporally variable parameter, they can be applied to instantaneous data, such as the type of data we collect in SEI monitoring (Montana DEQ 2017). The population scale median value (9.3 mg/l) was above the major stress assessment point of 8.0 mg/l. However, around 14% of the stream resource in the park was below this (Table 12; Figure 20) during late summer base flow in 2007–2009. Two specific sites with lower dissolved oxygen were on tributaries to Railroad and Rubideau Creeks. None of the park's streams were below the minor stressor level of 4.0 mg/l (this smaller concentration of dissolved oxygen is the lower stress disturbance assessment point because adult fish need less dissolved oxygen). Some stream reaches in the park naturally lack canopy (in burns or alpine areas) and dissolved oxygen may be somewhat reduced in the heat of the day at these sites. These reaches would (perhaps temporarily) not support young salmonids, yet we do not consider such naturally caused low levels of DO problematic. However, a

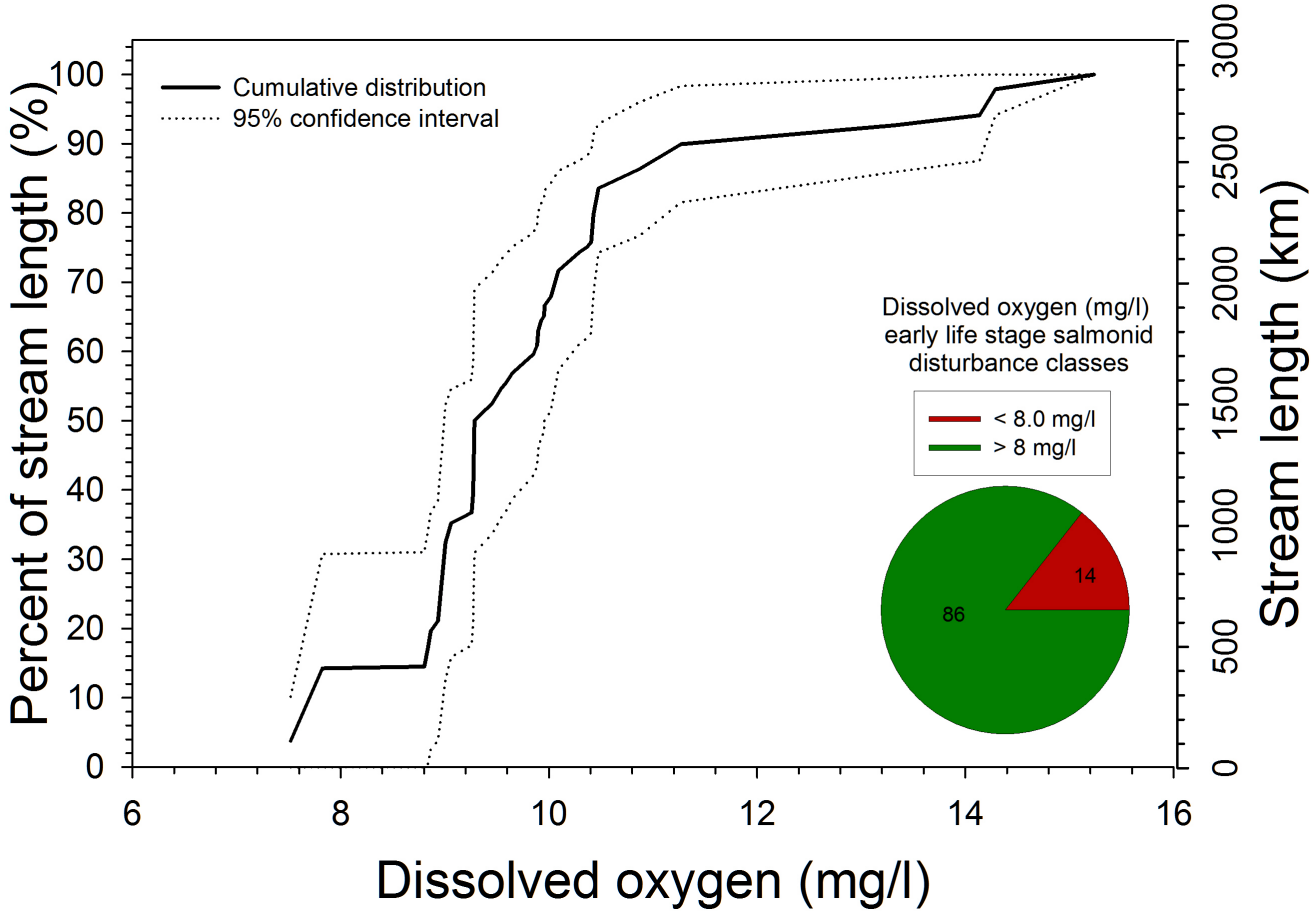


Figure 20. Cumulative distribution of instantaneous dissolved oxygen (mg/l) in the population of Glacier National Park streams, 2007–2009. The left y-axis gives the percent of streams in the park and the right y-axis shows the actual estimated length of stream. A 95% confidence interval (dotted lines) around the percent values (heavy line) is also shown. Pie chart shows the percentage of the total length in each stressor class as green (minor disturbance) and red (major disturbance). The assessment point is 8.0 mg/l—Montana Department of Environmental Quality criterion for early life stages of fish in Outstanding Resource Waters. Pie charts do not include a confidence interval for each estimate in these classes, so they should be used with caution.

small proportion of the stream reaches in or near the park with reduced oxygenation may be due to anthropogenic causes (Figure 21). Dissolved-oxygen levels are driven by several factors, including temperature, flow, and nutrient concentrations, all of which can vary with levels of human stress. However, additional data will be needed to conclusively connect diel, seasonal, and spatial patterns in dissolved oxygen to human stressors.

pH

The State of Montana establishes classification standards for ORW waters. The standards state that any induced variation of pH within the range of 6.5 to 8.5 must be less than 0.5 pH units, that natural pH outside this range must be maintained without change, and that natural pH above 7.0 must be maintained above 7.0 (Montana DEQ 2002). There is no manipulation of pH by the NPS within Glacier, and while there are complex interactions with other water chemistry parameters that can influence pH, some of which may have anthropogenic sources upstream or, in select cases, within Glacier, there is no evidence that pH at any sampled site was not "natural." Median pH in the park (Table 12a) was somewhat basic (8.2), matching the dominant anion (bicarbonate, see below) and the weathering of carbonate minerals from the sedimentary rocks that dominate the park. We do not use ecoregional assessment points for pH given a likely nonlinear response to disturbance and important assumptions about the directionality of how condition relates to a stressor parameter for this assessment point. Future assessment will include comparisons of the distribution of pH to see if there are statistical shifts across time that can be associated with changes in condition.

Specific conductance

Specific conductance ranged from 28 to 462 µS/cm, with a median of 144 (Table 12a). In general, lower order (smaller) stream sites in the park were more dilute when sampled at base flow, often with conductance well below 100 µS/cm. There are no explicit Montana DEQ regulatory criteria for specific conductance for Glacier's streams. Given an expected linear response between increasing conductance and stress in Glacier streams, we developed ecoregional assessment points to help put specific conductance in the park in context. A major stress assessment point of 284 µS/cm was exceeded in around 5% of the park's streams, with 59% below a minor stress level of 163 µS/cm, and the balance of about 36% in moderate stress, with conductance between the two assessment points. This suggests that most of the Glacier streams were as dilute as the best sites in the surrounding ecoregions. However, as noted, ecoregional assessment points are arbitrary and more work, especially repeated sampling, is needed to fully interpret them.



Figure 21. Monitoring site on a tributary to Railroad Creek located just outside Glacier National Park's southeast boundary. This site had reduced dissolved oxygen levels at the time of our sample (7.5 mg/l, or just below the state criteria of 8.0 mg/l). The site is adjacent to a highway (the stream is located down the road embankment shown in the lower image – see also Figure 41b). (NPS/BILLY SCHWEIGER)

Water temperature

Water temperature is a fundamentally important component of stream condition in Glacier (i.e., Jones et al. 2014). Stream water temperature appears in bioassessment models developed for Glacier's macroinvertebrate and diatom communities (see 3.8.3.1 and 3.8.3.2). This has important implications, especially given the ongoing loss of glacier meltwater-fed systems (Rood et al. 2005). Muhlfeld et al. (2011, 2016) and Jordan et al. (2016) recently showed compelling evidence that climate change links the fate of glaciers and endemic macroinvertebrates like the meltwater stonefly, *Lednia tumana*, in Glacier – likely due to shifts in water temperature

extremes and phenology. Under a future (yr. 2030) warming induced glacier and snowfield loss climate scenario, the projected distribution of *L. tumana* was shown to dramatically contract, with predicted loss of over 80% of its current range.

Midday base flow late summer instantaneous stream water temperature (hereafter "stream temperature") ranged from around 5 to almost 17 °C, with a population scale median of just under 10 °C (Table 12a). There are no relevant regulatory assessment points for our survey generated water temperatures; however, these values match general expectations for base flow midday instantaneous values in Glacier. Evaluation of stream temperature criteria is complex and should only be applied to temporally well-replicated data (i.e., not instantaneous values from survey events with a large temporal component of variance and a poor signal to noise ratio; Table 12a). Mills et al. (2011) present temporally replicated temperature data collected from the North Fork of the Flathead in 2007–2008. We also conduct more detailed analyses, including select time series of longer term stream temperature at sentinel sites in the sentinel site report by Schweiger et al. (in preparation a). In these models we compare stream temperature time series at sentinel sites to bull trout and other species temperature optima (ecological threshold assessment points). Finally, we develop a model of the drivers and key independent variables to stream water temperature in section 3.6.4.1 below.

Signal : noise
The ratio of signal to noise was low for temperature and dissolved oxygen, suggesting these parameters may have high levels of variation within a site. *In situ* water chemistry can vary strongly over 24 hours (driven by temperature, fluctuation in discharge, or from biochemical processes; Nimick 2003) and it is not a surprise that the quality of some of these indicators may be low for our survey approach. The high temporal variance suggests that natural gradients in diel cycles in solar insolation, elevation, discharge, and stream size may need to be controlled for or considered when interpreting these parameters. Interestingly, S:N was acceptable for pH and surprisingly high for conductance, perhaps reflecting the dilute nature of most Glacier streams and the fairly uniform geologic types in the park.

3.6.3.2 Major ions

We measured nine inorganic ions at SEI sites across the park (Table 12b). These responses are driven by chemical reactions with naturally occurring surficial geology and there is little regulatory context for them. The only Montana DEQ criterion available as an assessment point is for fluoride. SEI samples were not properly analyzed for this constituent until 2009, and our sample size is thus too small to assess. Nevertheless we doubt that there are any problematic concentrations of fluoride across the park. Mast (2007) also showed low concentrations at specific sites in the park.

Bicarbonate, calcium, and magnesium
Important naturally occurring ions included bicarbonate, calcium, and magnesium. Carbonate minerals in the sedimentary rocks found across the park are the likely source for these (Mast 2007). There are no relevant assessment points for these. With little connection to human disturbance, and levels as expected given the geology of Glacier, we do not estimate ecoregional assessment points.

Alkalinity
Alkalinity (composed of two major ions, commonly known as buffering capacity) measures the capacity of water to neutralize acid. Natural levels of alkalinity are important because they protect or buffer against rapid pH changes, which can be harmful to aquatic life. We measure alkalinity as the concentration of calcium carbonate (CaCO3). Sources for these ions are generally natural, including carbonate rocks (including limestone) and ion exchange reactions in stream catchments – although some wastewater contains high levels of carbonates from cleaning agents and food residue. Prior to effective controls of acid rain in the mid-1970s, alkalinity often varied with levels of sulfuric acidic emissions (Likens et al. 1977; Schindler 1988), with alkalinity levels increasing due to accelerated weathering and dissolution of carbonates (Kaushal et al. 2013). There are no regulatory criteria for alkalinity, although the EPA (2009) informally recommends a minimum value of 20 mg/l (except where it is "naturally lower" in areas with lots of granitic geology, which can occur in parts of Glacier). Alkalinity in Glacier in 2007–2009 was variable, ranging from 12 to 248 mg/l with a population scale median of 152 (Table 12b).

To better understand alkalinity in Glacier streams in the context of its ecoregion, we estimated ecoregional assessment points. This parameter generally meets our assumptions for this type of assessment. Some alkalinity is important to stabilize acidity levels, but in excess, it can result in a range of effects, including hard water, ammonia toxicity, and algal blooms (Kaushal et al. 2013). A major stress ecoregional assessment point of 144 mg/l was exceeded in around 4% of the park's streams, with 68% below a minor stress level of 99.5 mg/l, and the balance of about 28% in moderate stress (Figure 22). These results suggest that only a small amount of stream in the park has alkalinity higher than the most stressed reference sites surrounding the park. Most stream sites in the park are well buffered, likely reflecting longer

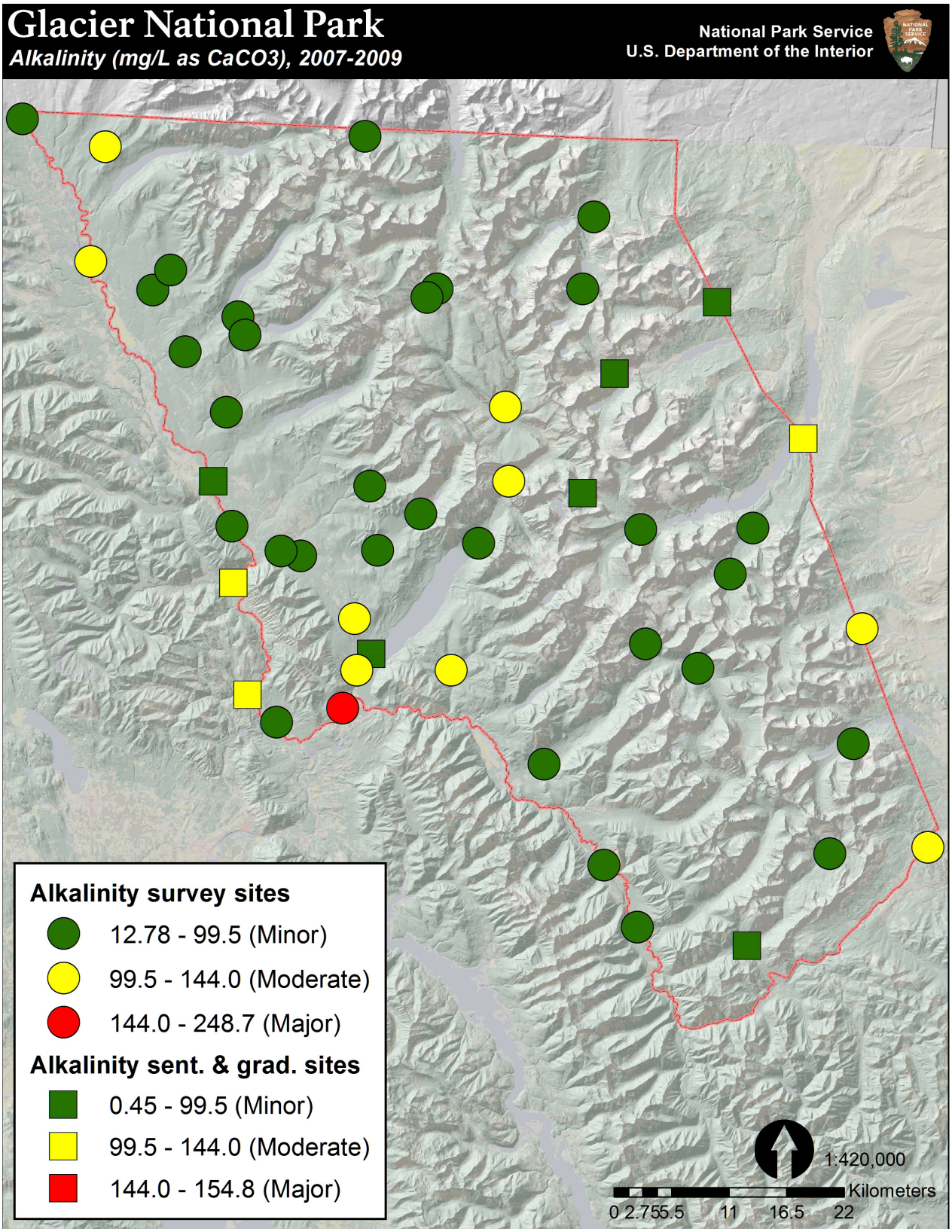


Figure 22. Map of alkalinity (mg/l of CaCO3) at Stream Ecological Integrity survey sites and sentinel (sent.) and gradient (grad.) sites in Glacier National Park, 2007–2009. Colored disturbance classes are based on assessment points defined from ecoregional stream sites in an expected or, a priori, reference state in the park and its surrounding ecoregions. Red indicates sites with the highest concentrations. See Appendix A for a complete list of site numbers and names.

hydrologic flow paths and greater opportunity for rock–water interactions, especially in larger river basins (Mast 2007; Mills et al. 2011). Note our application of ecoregional assessment points may be over simplified in this case. Extremely low levels of alkalinity can also be problematic (suggesting a nonlinear relationship with stress), especially if acid rain is present. These types of streams can occur in the park, largely in catchments with stoichiometrically inert substratum and extremely dilute pristine waters (see Ellis et al. 1992 for a discussion along these lines for remote lakes). Therefore these assessment points are best viewed with caution and only as baselines for future comparison.

Sulfate and chloride

Sulfate and chloride are both important constituents of stream water. They have several natural sources, including bedrock and atmospheric deposition (i.e., from volatized ocean salt water spray). However, they are also indicators of anthropogenic disturbance in a site's catchment (Peters 1984; Biggs et al. 2004), reflecting contributions from a wide range of stressors, including agriculture, mining, and urban land use. There are no known or likely meaningful point sources for these constituents in or close to the park; however, they can both be volatilized from external human sources and distributed to streams and rivers in the park via atmospheric deposition. Chloride is also often used in salts applied to roads (Thunqvist 2004; Kelly et al. 2007) and can join runoff into streams, having strong effects on macroinvertebrates (Blasius and Merritt 2002). Sulfate is released from oxidation of sulfide minerals in mine wastes and tailings ponds; should the long debated mining ever occur in the Canadian portion of the North Fork of the Flathead, the river could be impacted by sulfate.

Both chloride and sulfate concentrations generally were low in Glacier in 2007–2009, with park scale maxima of 3.8 and 10.9 mg/l, respectively (Table 12b, and for chloride, Figure 23). Montana DEQ and EPA have been developing

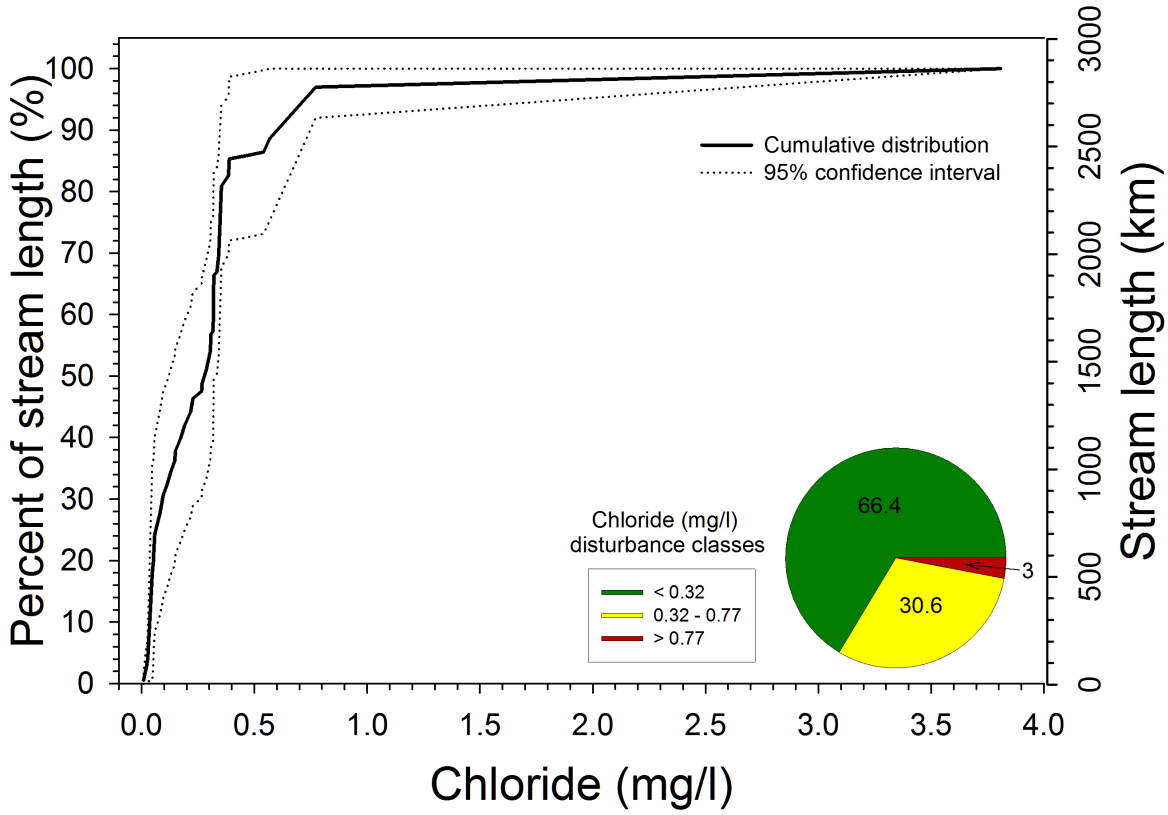


Figure 23. Cumulative distribution of chloride (mg/l) in the population of Glacier National Park streams, 2007–2009. The left y-axis gives the percent of streams in the park and the right y-axis shows the actual estimated length of stream. A 95% confidence interval (dotted lines) around the percent values (heavy line) is also shown. Assessment points are derived from reference sites in the park and its surrounding ecoregions at the 95th (0.77) and 75th percentile (0.32). Pie chart shows the percentage of the total stream length in reference (dark green), intermediate (yellow), and non-reference (red) classes based on comparisons with ecoregional assessment points. Pie charts do not include a confidence interval for each estimate in these classes, so they should be used with caution.

guidance for chloride criteria, but as of this publication, there were no final rulings (and none planned for sulfate). When the chloride criterion is available, we will apply it to SEI data. However, given possible general utility as indictors of stream condition and expected linear relationships with stress, we developed ecoregional assessment points for both chloride and sulfate. Using these ecoregion thresholds, approximately 3 and 4.5% of the park's waters were in a major disturbance class for chloride (>0.77 mg/l) and sulfate (>8.6 mg/l), respectively. Approximately 66 and 77% of the park's waters were in a minor disturbance class for chloride and sulfate (with the remainder of the park's streams in a moderate stress state). Importantly, these ecoregion assessment points reflect the relatively pristine state of the streams in and around Glacier and are conservative. For example, now dated EPA (2009) criterion for chloride based on toxicity for plant, fish, and invertebrate species was 230 mg/l (which would easily place all of Glacier's waters in a minor disturbance class in 2007–2009). Mast (2007) suggests that atmospheric deposition from largely natural sources is probably the dominant source of chloride, with most sulfate in the park's streams from natural sources such as weathering of sedimentary rocks. Mast (2013) summarizes patterns across several benchmark sites across the United States, indicating that sulfate in stream water from human sources decreased from the mid-1960s to 2010, likely due to regulation from the Clear Air and Clean Water Acts. Nevertheless, any changes in land use in and around the park or shifts in the anthropogenic contribution to deposition might elevate chloride or sulfate. Our ecoregional assessment points will serve as useful baselines values for future comparison should this occur.

Signal : noise

Signal to noise was acceptable for most inorganic ions. Sodium had values below our rough threshold of 1.0, suggesting this parameters may have high levels of variation within a site. However, overall, most are likely relatively well suited to sampling and interpretation within a survey context of episodic base flow sampling only.

3.6.3.3 Total suspended sediment

Total suspended sediment (TSS) is a direct measure of the amount of particulate matter in a stream. It is important, influencing other parameters such as nutrient levels (see next section below) and can have a direct impact, leading to degradation of aquatic habitat. Specifically, suspended sediment in spawning areas can cause a reduction in fish embryo survivorship (Confederated Salish and Kootenai Tribes and Montana Fish, Wildlife & Parks 2004). TSS has largely natural sources in Glacier, such as soil slump and natural bank erosion (Mast 2007; Mills et al. 2011). Wildfire in the park and associated management activities can also cause often high, but transitory, levels of TSS (Mast and Clow 2008). However, select point disturbances, especially from roads, and complex larger sale indirect interactions between land use, climate, and hydrology might link TSS to human source(s) in or near the park (British Columbia Ministry of the Environment 1978; Flathead River North Fork Study Board 1988; Dalby 1983; Appleman et al. 1990; Gildea et al. 2004).

Base flow TSS levels in 2007–2009 ranged from 1.2 to 26 mg/l, with a population scale median of 1.2 mg/l (Figure 24, Table 12b). These base flow values are all likely low relative to what can occur during runoff at most sites. During high-flow conditions, sediment loads naturally increase, dramatically reflecting greater kinetic energy for erosion and transport (Hem 1992; Horowitz 2008). For example, sampling during runoff in 2008 on the North Fork of the Flathead at our sentinel site and a survey site near the southwest corner of the park near where the river crosses the boundary had high concentrations (319 mg/l and 308 mg/l, respectively; Mills et al. 2011). Nearly all of the major western tributaries of the North Fork of the Flathead have been previously listed on Montana's 303(d) list as impaired for cold water fisheries owing to sediment loading associated with erosion of unpaved roads in the catchments to the west and outside of the park. We sampled several of these streams in 2007 as they entered the park. At least at base flow in 2007 and 2008, these streams no longer had high levels of TSS. Adoption of "Best Management Practices" for timber harvesting and forestry roads in the North Fork Basin, as well as reclamation of clear-cut areas, has likely reduced the associated effects on water chemistry (Hauer et al. 2007). We present more data on TSS that attempts to capture some of these and other temporal patterns in Schweiger et al. (in preparation a).

There are no regulatory criteria for TSS. Given the importance of sediment in streams, Montana DEQ (Kusnierz et al. 2013) has created related criteria for sediment size and embeddedness (degree to which larger substrates are impacted by fines and sands) as measured in our physical habitat methods (see section 3.7 below). We expect TSS has a largely linear response with increasing stress and we therefore developed ecoregional assessment points to help interpret TSS in the park. A major stress assessment point of 6.7 mg/l was exceeded in around 12% of the park's streams, with 70% below a minor stress level of 1.7 mg/l, and the balance of about 18% of the park's streams in moderate stress, having TSS

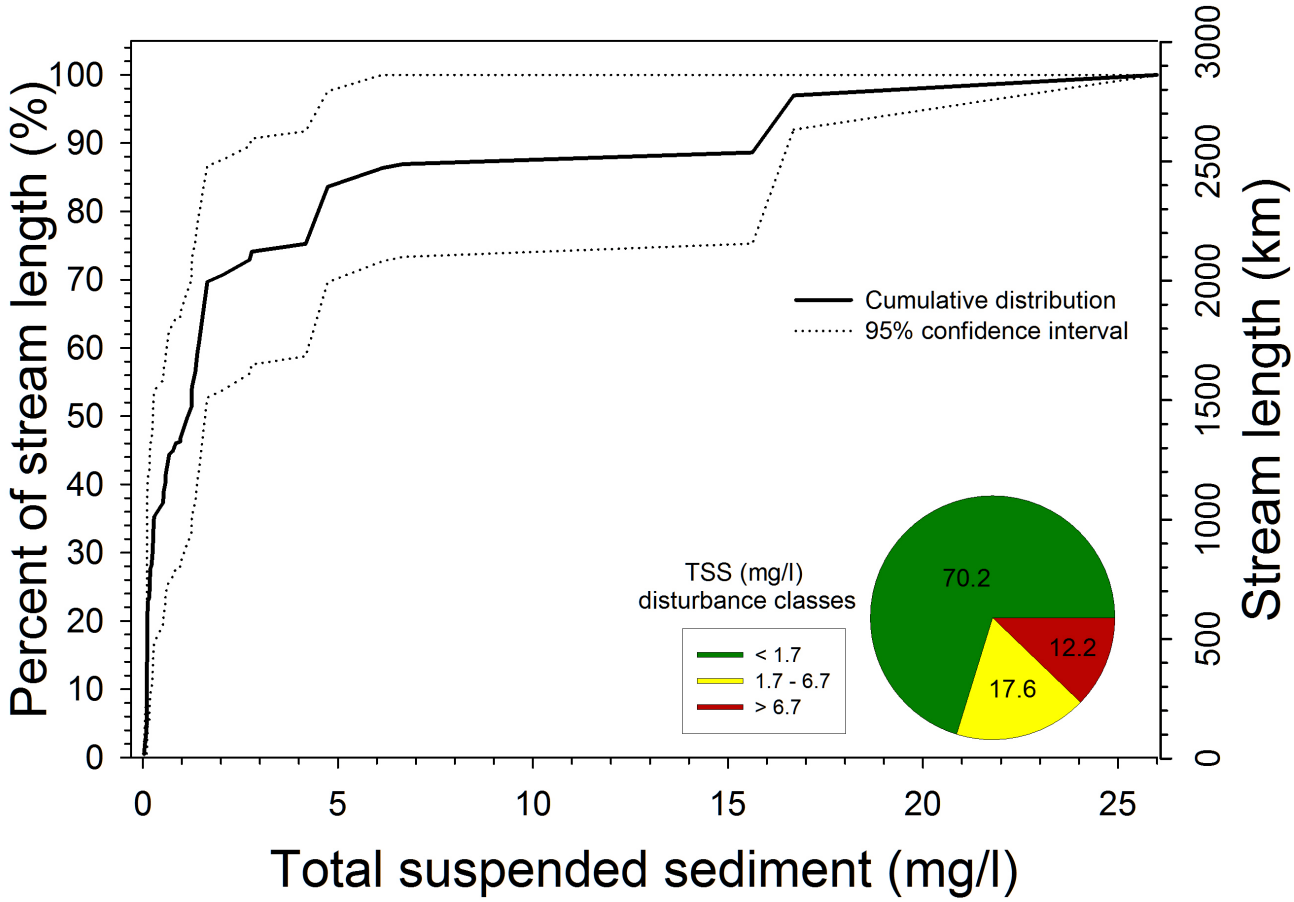


Figure 24. Cumulative distribution of total suspended sediment (TSS) (mg/l) in the population of Glacier National Park streams, 2007–2009. The left y-axis gives the percent of streams in the park and the right y-axis shows the actual estimated length of stream. A 95% confidence interval (dotted lines) around the percent values (heavy line) is also shown. Assessment points are derived from reference sites in the park and its surrounding ecoregions at the 95th (6.7) and 75th percentile (1.7). Pie chart shows the percentage of the total length in minor (dark green), moderate (yellow), and major (red) disturbance classes based on comparisons with ecoregional assessment points. Pie charts do not include a confidence interval for each estimate in these classes, so they should be used with caution.

between the two assessment points. These assessment points are low and reflect base flow sediment loads in low stress (reference) caliber streams in the largely wilderness areas surrounding the park. Most Glacier streams had low TSS and were as dilute as the best sites in the surrounding ecoregions. However, select sites may have had excess TSS and associated bed sediments (see 3.7.3.4) caused by nearby human land use (Figure 25, Figure 26). While more work is needed to better understand these patterns, it is likely that they have a relatively small localized effect on stream condition.

Signal : noise

TSS had S:N values below our rough threshold of 1.0, suggesting a high level of variation within a site. This is not surprising given the importance of highly volatile stream discharge in sediment loads, and TSS sampled in a survey context should be interpreted with caution.

3.6.3.4 Nutrients

Nutrients, primarily nitrogen (N) and phosphorous (P), but also carbon (C) (i.e., Goldman et al. 1971), are essential for stream ecosystem function. However, elevated concentrations (eutrophication) can cause a variety of problems, including degradation of ecosystem integrity and recreational activities, and impacts to human health (Dubrovsky et al. 2010). Both natural and anthropogenic drivers affect nutrient concentrations in streams. Natural factors include soil and groundwater characteristics, hydrology, *in situ* production, and the chemical properties of the nutrients themselves. Human activities can accelerate eutrophication



Figure 25. Stream Ecological Integrity site on McDonald Creek located along Going to the Sun Road in Glacier National Park, 2008. This site had higher levels of total suspended sediment and embedded streambeds (bottom image). (NPS/ BILLY SCHWEIGER)

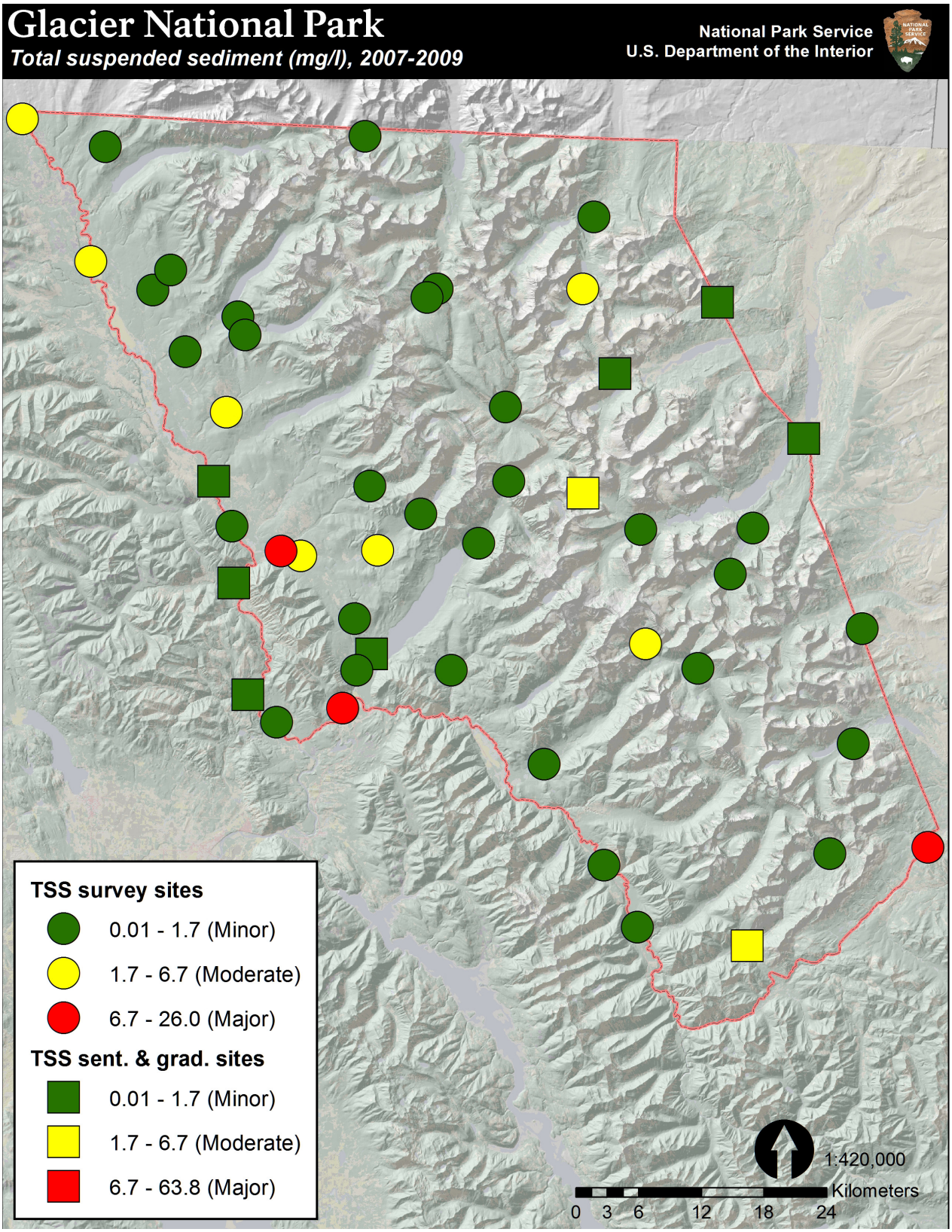


Figure 26. Map of total suspended sediment (TSS) (mg/l), at Stream Ecological Integrity survey sites and sentinel (sent.) and gradient (grad.) sites in Glacier National Park, 2007–2009. Colored disturbance classes are based on assessment points defined from ecoregional stream sites in an expected or a priori reference state in the park and its surrounding ecoregions. Red indicates sites with the highest concentrations. See Appendix A for a complete list of site numbers and names.

via increased atmospheric deposition, agricultural and urban runoff, leaking septic systems, sewage discharges, and eroded stream banks (Ellis et al. 2015; EPA 2016c). Recent work by the EPA and its partners (including the NPS) suggests that in 2008–2009, excess nitrogen and phosphorous were some of the more important stressors on streams, with 40 to 50% of stream length nationwide in poor condition due to N and P levels, respectively (EPA 2016c).

Nutrients collected at SEI events in Glacier included several forms of nitrogen (ammonium, nitrite + nitrate, total nitrogen), phosphorous (total and biologically available orthophosphate), and organic carbon (Table 12c). We include multiple analytes of N, P, and C in the SEI protocol such that we can better understand often complex interactions between specific ecological responses and a particular form of a nutrient. For example, the native nuisance algae *Didymosphenia geminata* may be influenced by ultra-low amounts of organically available phosphorous, as well as total nitrogen, depending on the location (see 3.8.4.3, Schweiger et al. 2011; Bothwell et al. 2014). However, following recent guidance by Montana DEQ (Suplee and Watson 2013), we restrict our assessment in this report of potential stress on Glacier streams to total nitrogen and phosphorous.

We include "trigger" values in Table 12c as defined by Montana DEQ (2017). These are limits to anthropogenically caused changes in a parameter allowed in outstanding resource waters (ORW – all of Glacier's streams and rivers). This survey report does not include estimates of change, so these are not entirely relevant here. However, each trigger value is less than the range across our survey sites. Even though we suspect almost all of the variance in nutrient concentrations in the park is due to natural causes, the low trigger values do show how small of a human caused change in ORW waters would be allowed by Montana DEQ.

Nitrogen and phosphorus concentrations in streams have the interesting quality that as they increase they may initially enhance certain stream characteristics (e.g., cause fish to grow larger), but then, at higher concentrations, lead to conditions that can reduce ecological condition (e.g., result in low dissolved oxygen that impairs a fishery). This non-linear response with stress is in part why we do not develop ecoregional assessment points for nutrients. Setting numeric nutrient criteria requires an understanding of how eutrophication progresses with increasing nutrient concentrations, and at what point the detrimental effects begin to occur. Montana DEQ has developed a set of nutrient criteria (for N and P) that differ from EPA or previous state criteria in several useful ways (Suplee et al. 2008; Suplee and Sada de Suplee 2011; Suplee and Watson 2013). They are specific to summer months (July to September), when stream ecosystems are often most stressed due to low flow conditions and elevated temperature. They vary by ecoregion, with different values in regions where nutrients are naturally elevated. Finally, they are derived from a modeling exercise comparing nutrient data to biological response (and as such are more like ecological thresholds).

In general, concentrations of all nutrients, including total N and P, were low and near or below detection limit (Figure 27, Figure 28, Table 12c). Using Montana DEQ criteria as a major disturbance assessment point, approximately 13 and 12% of the park's waters had concentrations above the regulatory criteria of 0.325 mg/l for total N, and 0.025 mg/l for total P, respectively. With no intermediate criteria defined, approximately 87 and 88% of the park's waters were in a minor to moderate disturbance class for these two nutrients.

There are limited site specific anthropogenic causes of elevated nutrients in Glacier. This may include septic tank effluent from some inholdings on lower Lake McDonald (Hauer et al. 2007) that might affect local tributaries to the lake (we have sites on two of these). There may also be interactions with groundwater from leakage from the water supply to park headquarters on Rubideau Creek (NPS 2002) that might elevate nutrient concentrations. Finally, sites located near roads, especially on the park's boundary, might receive nutrient rich runoff. Importantly, our bioassessment models (see section 3.8 below) suggest it is unlikely that these potential anthropogenic nutrient disturbances are having any meaningful effect on the ecological condition of associated water bodies.

Overall we suspect that elevated nutrient concentrations found in the park are natural in their source(s). For example, Stanford et al. (1994) demonstrated that dissolved nitrate can concentrate in the center of undisturbed alluvial aquifers in the park, with 12-17% of the base flow nitrate load of the river downstream from the aquifer derived from nitrification within the aquifer. They also demonstrated that organically available phosphorus can be up to an order of magnitude higher in floodplain groundwater. High solute loads in groundwater can discharge into surface waters, producing intense zonation in nutrients (revealed by localized mats of green algae, such as *Ulothrix zonata*; Figure 29). There is also good evidence for fires leading to temporary changes in stream chemistry, with post-fire leaching of nutrients to surface water (particularly nitrate) commonly observed

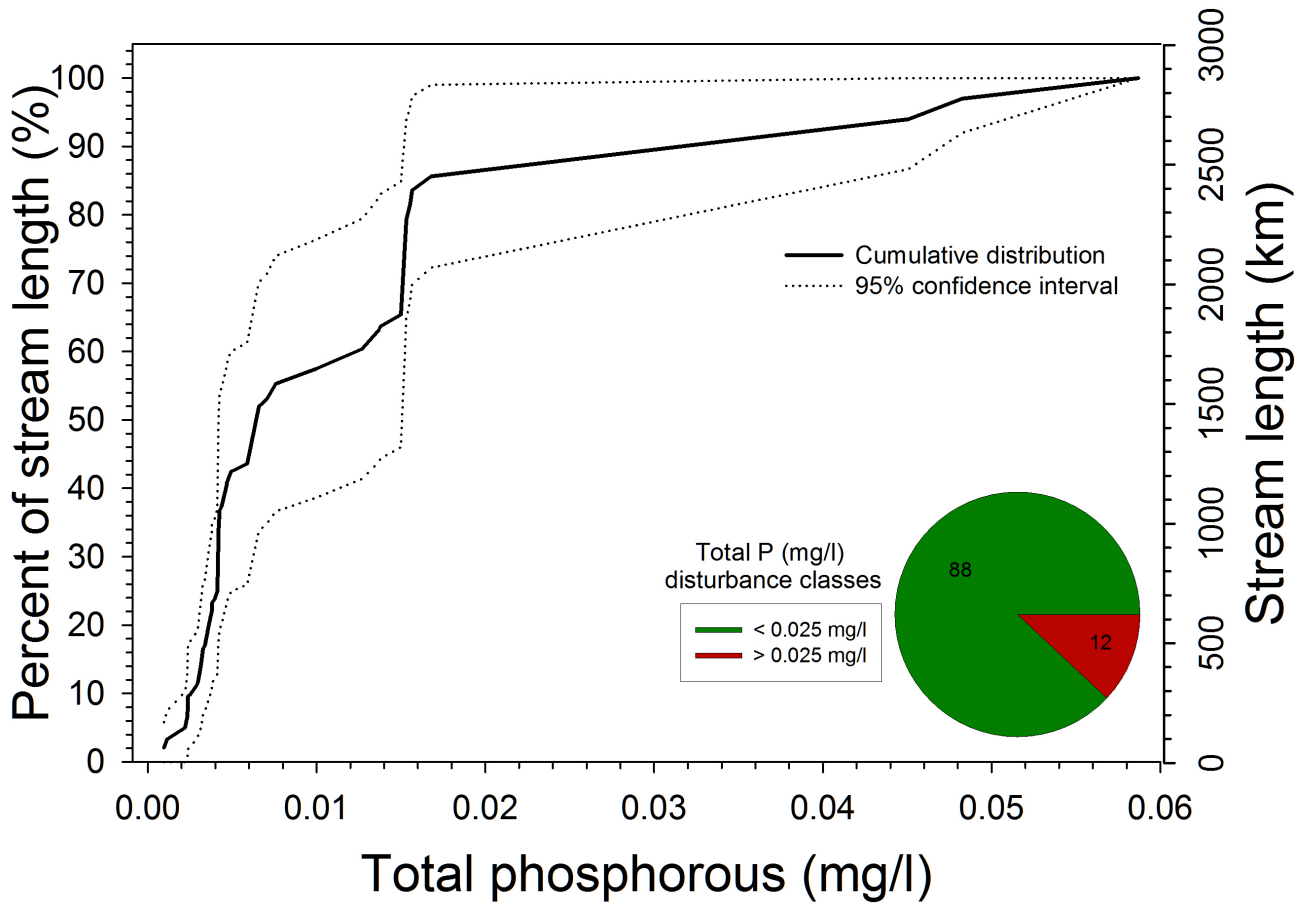


Figure 27. Cumulative distribution of total phosphorous (P) (mg/l) in the population of Glacier National Park streams, 2007–2009. The left y-axis gives the percent of streams in the park and the right y-axis shows the actual estimated length of stream. A 95% confidence interval (dotted lines) around the percent values (heavy line) is also shown. Assessment points are derived from Montana DEQ criterion of 0.025 mg/l. Pie chart shows the percentage of the total length in minor disturbance (dark green) and major disturbance (red) classes based on comparisons with the ecoregional assessment point. Pie charts do not include a confidence interval for each estimate in these classes, so they should be used with caution.

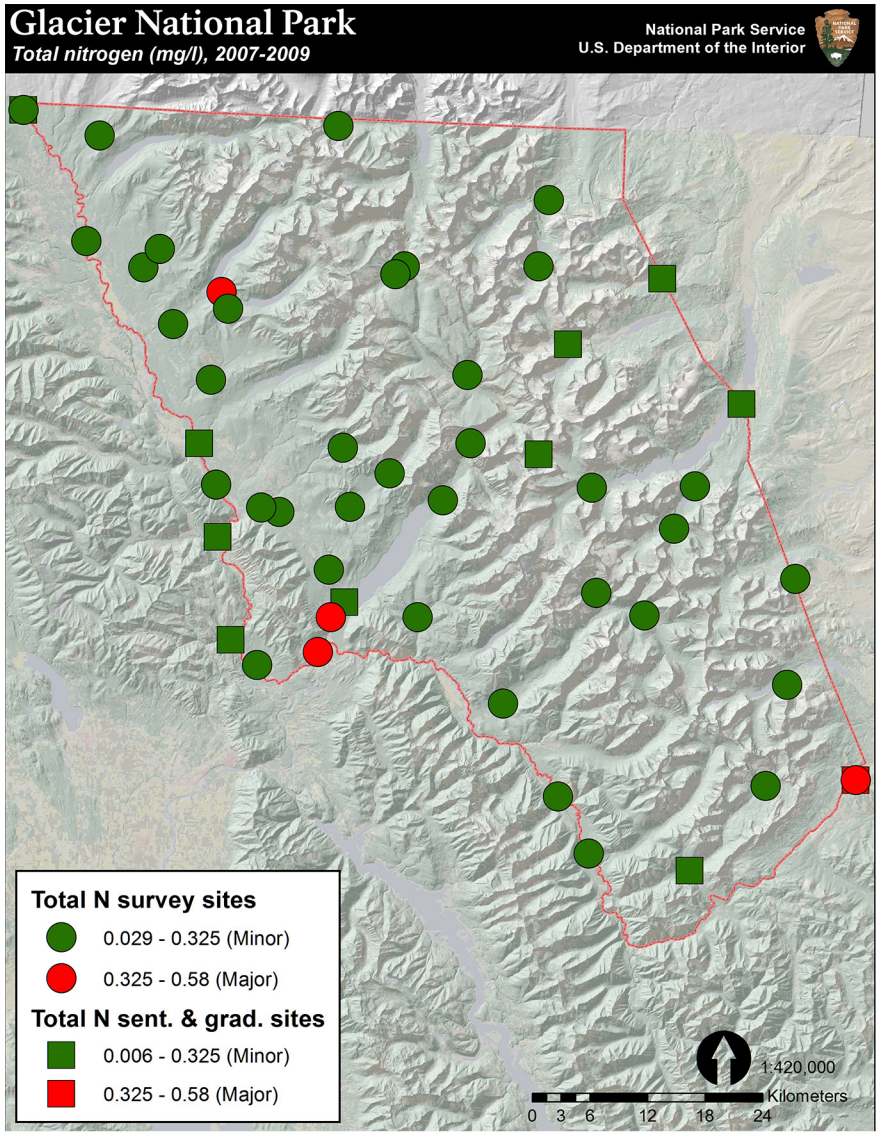
in the first or second year following a fire (Mast and Clow 2008). While the most recent fire in the catchment of an SEI site was in 2003 (that we then sampled in 2007), it is possible that elevated total nitrogen concentrations in select sites in the North Fork basin were residual impacts from these fires. Moreover, we present a model of total phosphorous concentrations in the park below that, in its final form, only includes natural independent variables (i.e., we included as potential predictors variables like HDI). Draft models of total nitrogen, not included in this report, are much the same.

Montana DEQ integrated nutrient assessment; Network SEI approximation

Because our estimate that 12-13% of the park's waters are in a major stress category may be confounded with natural drivers, we applied an approximation to a more comprehensive Montana DEQ nutrient assessment protocol as follows.

Montana DEQ provides a detailed protocol for comprehensive evaluation of possible nutrient issues (Suplee and Sada de Suplee 2011). The Montana DEQ method requires a minimum sample size during a growing season (to establish a regulatory exceedance for N or P, a 12-sample minimum is recommended). It also uses a tiered approach with nutrient concentration (total N and P) and a series of support criteria for algae-based productivity (chlorophyll-a, ash free dry mass), a diatom nutrient increaser metric, and a macroinvertebrate nutrient indicator metric. Montana DEQ provides tools for statistical evaluation of nutrient concentrations and a decision rule for how various combinations of data are assessed to determine if there is a potential nutrient issue at a site.

While the SEI protocol provides many of the inputs to this approach, we lack sufficient replicates of nutrient concentra-



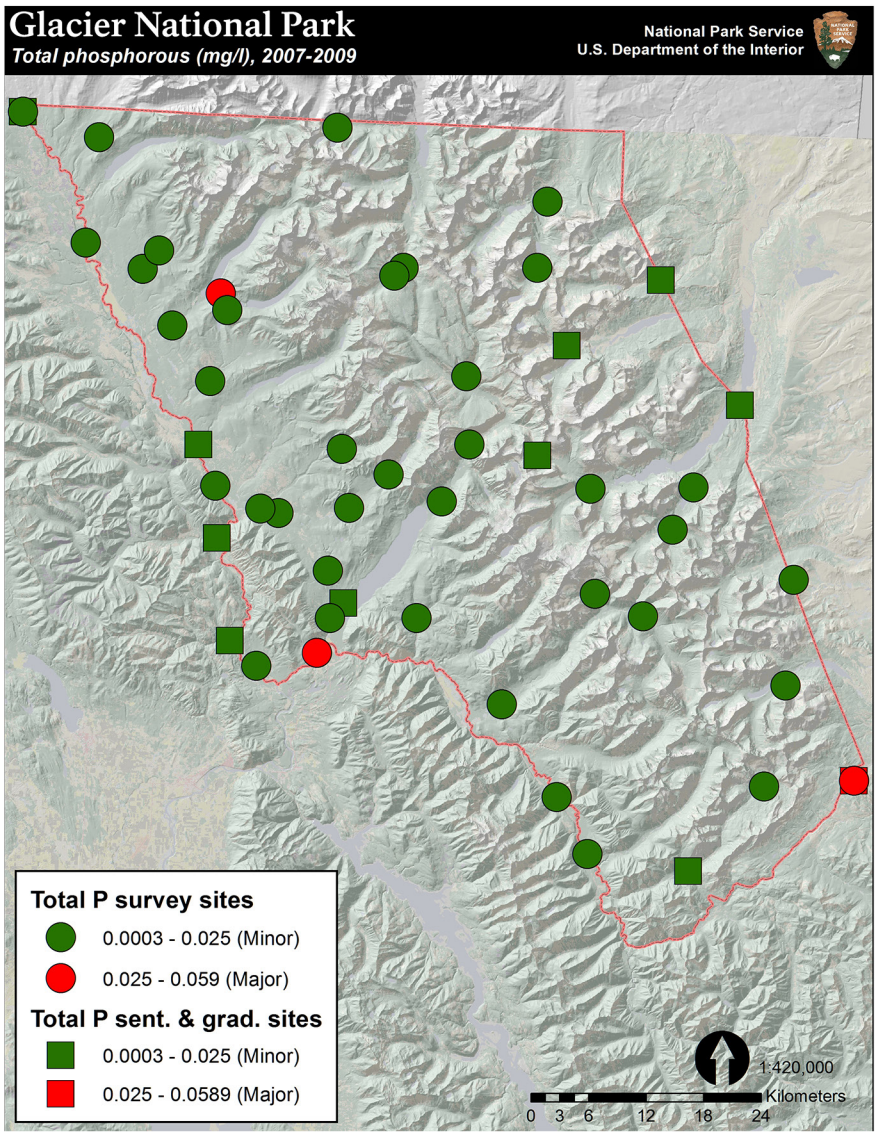


Figure 28. Maps of total nitrogen (N) and total phosphorous (P) (mg/l), at Stream Ecological Integrity survey sites and sentinel (sent.) and gradient (grad.) sites in Glacier National Park, 2007–2009. Colored disturbance classes are based on assessment points defined from Montana DEQ regulatory criteria (Suplee and Watson 2013). Red indicates sites with concentrations above a major disturbance assessment point, with green indicating sites below a minor disturbance level. See Appendix A for a complete list of site numbers and names.

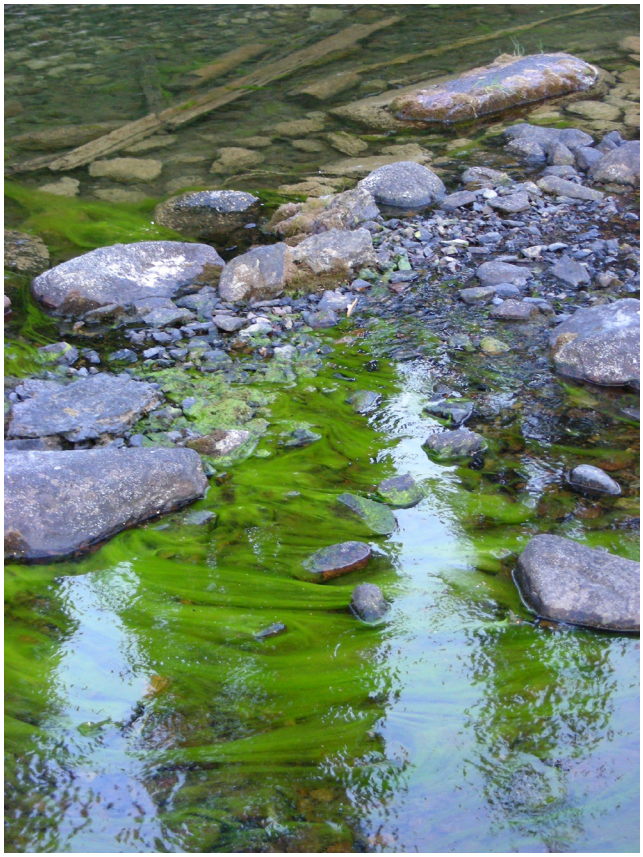


Figure 29. Algal bloom, (probably *Ulothrix zonata*), on the lower Quartz Creek in Glacier National Park, 2007. The bloom was likely caused by groundwater upwelling from deep floodplain aquifers (a common natural source of spatial variability in water chemistry, Hauer et al. 2007). (NPS/BILLY SCHWEIGER).

tion samples and can only apply an approximation of the full method to our survey data. We do include the requirement of the presence of a known or likely anthropogenic source (Montana DEQ uses a similar assumption in its assessment process; Suplee et al. 2005; Kusnierz et al. 2013). Table 12c presents the summary of this method applied to Glacier survey data from 2007–2009. One site failed - Rubideau Creek, located downstream of the park's water supply system (NPS 2002). Given the proximity of a utility with known issues, nutrient levels in Rubideau Creek could have a human cause. Design based estimates infer a human caused major stress category to about 8% of the park's stream length.

Note that our sentinel site data are a better fit to the Montana DEQ nutrient protocol, and we apply the criteria with fewer caveats in Schweiger et al. (in preparation a).

Signal : noise

Signal to noise was acceptable for most nutrients, with the exception of ammonia, ash free dry mass and chlorophyll-a, which were below 1.0. Total P was also marginally acceptable, with an S:N score of 1.5. Thus, somewhat surprisingly, most nutrients may be relatively well suited to interpretation within a survey context.

3.6.3.5 Metals (trace elements) in water

In 2007–2009 we analyzed all samples for total metals (i.e., from unfiltered samples), given Montana DEQ aquatic-life standards for total, rather than dissolved, concentrations (except aluminum which has a dissolved fraction criteria). However, it is primarily the dissolved form that causes aquatic toxicity more relevant to long-term ecological monitoring, and the EPA has recommended that criteria for metals be re-expressed as dissolved concentrations (EPA 1996). Future work should include both total and dissolved metal results for Glacier should we continue to monitor metals in the park (as done in our other parks, see Schweiger et al. 2014a, b).

Overall metals in the streams of Glacier were of little concern. Very few events had detectable metal concentrations, and no median values were above any assessment point (Table 12d). Importantly there is usually a strong season effect in the concentrations of trace elements, with peaks in April, May, and June reflecting greater sediment transport by rivers during snowmelt. Given the neutral to basic pH of most water in the park, the base flow timing of our survey sample events, and the lack of mining or urban sources, low metal concentrations are expected. As with nutrients, "trigger" values defined by Montana DEQ (2017) are reported. These are limits to anthropogenically caused changes in a parameter allowed in outstanding resource waters (ORW – all of Glacier's streams and rivers). They show how small of a human caused change is allowed by Montana DEQ in ORW waters. Trigger values for metals were generally less than the range in results across our survey sites, suggesting that most of the variance in metals concentrations in the park is due to natural causes.

Iron and manganese did occur in high concentration at one event, resulting in a small percentage of the population of streams in the park being above a human-health or chronic aquatic life criteria, respectively. The site with these high values was located on a tributary to Railroad Creek near the border of the park adjacent to a highway, and is somewhat atypical for Glacier (see Figure 21). It likely receives runoff from auto emissions and de-icing operations on the highway that might contain higher levels of metals.

Signal : noise

Because most data were non-detects, it was not possible to estimate signal to noise. It is likely that there is an important

temporal component in the very small metal concentrations across the park.

3.6.4 Exploratory models of water chemistry

Next, we present example models of water chemistry indicators and select environmental and disturbance variables that may predict or covary with patterns in the habitat response. We develop models for two parameters (temperature and total phosphorous), selected based on their general importance in the ecology of Glacier's streams and their possible management utility (additional models available from the network upon request). We selected the potential independent variables based on our collective ecological experience, statistical attributes, and those that might have the most utility for stream resource management in Glacier. For details on model construction, see the methods and/or the introduction to this same subject within the Human Disturbance section above.

3.6.4.1 Stream water temperature

Water temperature plays a key role in streams (i.e., Kishi et al. 2005; Isaak et al. 2016; Giersch et al. 2016; Jordan et al. 2016). Among other effects, the thermal nature of streams can change food web structure through direct and indirect trophic interactions, shift the distribution of species, and impact productivity. At the most basic level stream water temperature is largely a product of the physical system that controls (over the short term) weather and (over longer time frames) climate (Sinokrot and Stefan 1994). These drivers include air temperature, solar radiation, relative humidity, wind speed, cloud cover, and barometric pressure, in addition to stream geometry, stream flow, and inflow temperature. The interactions of climate change and stream water temperature is an active area of research (i.e., Isaak et al. 2017) given these fundamental relationships. While our SEI dataset is not a comprehensive take on the possible drivers of stream temperature in Glacier, constructing a simple model of the relationships among our estimates of water temperature in 2007–2009 and possible independent variables was useful to help isolate connections in our data that may support our bioassessment models and our general interpretation of patterns in the condition of Glacier streams.

The final model of base flow late summer midday instantaneous stream water temperature included nine independent variables (Table 13). It was highly significant ($p < 2.307e-07$), with an adjusted r^2 of 0.69, indicating a large proportion of the variation in stream temperature was accounted for in the model. Complete model details are presented in Appendix F. We focus our interpretation here on select variables in the model that either had high relative importance, low p-values, and/or interesting relationships as drivers or covariates of stream temperature. We use conditional plots of partial residuals to visualize the model (Larsen and McCleary 1972; Breheny and Burchett 2013).

Over 21% of the variation in stream temperature was explained by the date of the year the sample event occurred, with colder temperatures later in the year (Table 13, Figure 30). In most years such seasonal effects are typical (and why control for seasonality in long-term trend models is so

Table 13. Model of midday instantaneous stream water temperature in 2007–2009 during base flow later summer conditions at Glacier National Park. Final model selected using Akaike Information Criterion (AIC) and expert opinion from 24 candidate variables. Relative importance (Rel. Imp %) is the total amount of explained variance for each variable expressed as a percentage.

Model component	Estimate	SE	t	p	Rel. Imp. (%)
Intercept	-39.90	14.95	-2.67	0.01	–
Day of year	-0.07	0.01	-5.39	0.00	0.21
Elevation (m)	0.02	0.01	4.55	0.00	0.11
% glacier in catch. (log)	3.15	0.72	4.36	0.00	0.08
Max. air temp catch. (°C) (30yr)	3.57	0.80	4.46	0.00	0.12
Discharge (m^3/s) (log)	4.35	1.13	3.84	0.00	0.08
Mean embeddedness (%)	0.09	0.02	3.93	0.00	0.11
Mean canopy cover (%)	0.04	0.02	2.24	0.03	0.03
Mean depth (cm)	-0.15	0.03	-6.16	0.00	0.21
Relative bed stability (log)	2.66	0.67	3.99	0.00	0.05

Notes: SE = standard error of coefficient, t = t test value, p = probability of the t. Residual standard error: 1.59 on 30 degrees of freedom, Multiple R^2: 0.77, Adjusted R^2: 0.69, F-statistic: 11.05 on 9 and 30 DF, p-value: 2.307e-07.

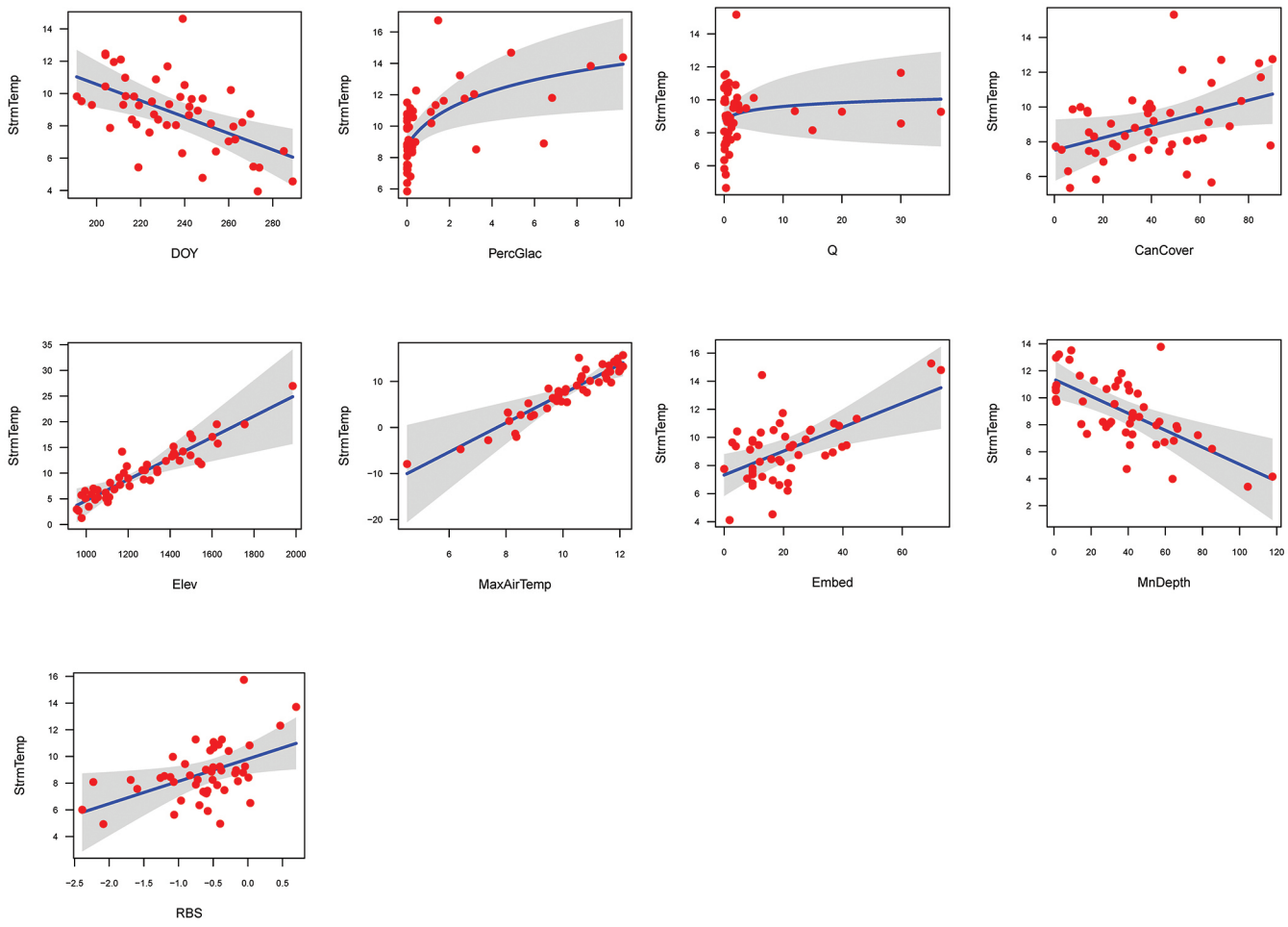


Figure 30. Partial residual plots of an exploratory model of Glacier National Park midday instantaneous stream water temperature (°C) during late summer base flow in 2007–2009. Conditional partial residuals show the relationship between each unique independent variable and stream temperature, with all other variables held constant at the median for numeric variables and most common level for factors. All variables are shown back transformed to their original scale as applicable. Plots of numeric independent variables include a best fit line and 95% confidence bands around this fit. Codes in figures are: StrmTemp = instantaneous stream water temperature (°C); DOY = day of year; PercGlac = percent of catchment as glacier; Q = discharge (m3/s); CanCover = mean canopy cover (%); Elev = elevation (m); MaxAirTemp = maximum 30 year air temperature in catchment (°C); Embed = mean embeddedness (%); MnDepth = mean depth (cm); RBS = relative bed stability. See the full model results in Appendix F and Table 13.

important). Including a seemingly obvious predictor like day of year is important as it removes this effect from the other independent variables in the model. Around 8% of the variance in stream temperature was accounted for by the log of stream discharge, with warmer temperatures in streams with higher discharge (note that because of the log, a unit increase in stream temperature can occur with a small increase in discharge). Given other variables in the model (i.e., elevation and stream depth) this suggests that warmer water in the streams of Glacier (at midday, base flow late summer 2007–2009) may have been a direct result in part from greater flow, or that this is not instead an effect of larger rivers occurring at lower elevations. An interesting predictor was the mean embeddedness of the sample reach, with an importance value of 11%. Sites with more embedded substrates tended to have warmer waters, although we suspect this is a complex interaction with the effects of discharge. Deeper channels had colder waters (relative importance of 21%). This is once again likely due to simple physics. Finally, in the context of the complete model (i.e., the bivariate relationship is not all

that compelling), we saw a strong positive effect of maximum air temperature over a 30 year period. This is likely the primary link between stream water temperature and shifting climate regimes and thus an ongoing focus of our and our partners' work on streams in Glacier.

3.6.4.2 Total phosphorous

The final model of total phosphorous concentration included eight independent variables (Table 14). It was highly significant ($p < 8.204e\text{-}10$), with an adjusted r^2 of 0.77, indicating most of the variation was accounted for in the model. Complete model details are presented in Appendix F. We focus our interpretation here on select variables in the model that either had high relative importance, low p-values, and/or interesting relationships as drivers or covariates of total phosphorous. We use conditional plots of partial residuals to visualize the model (Larsen and McCleary 1972; Breheny and Burchett 2013).

Our model of total phosphorous concentrations in 2007–2009 was dominated by two independent variables, total nitrogen concentration and total suspended sediment (Table 14, Figure 31), each of which had a relative importance of 34%. While the univariate fit for both of these is controlled somewhat by a few outliers (note that if these are removed the fits are still relatively strong and positive), it is clear that total phosphorous concentrations increase with total nitrogen and total suspended sediment. Stoddard et al. (2016) shows that across broad spatial scales, the concentrations of nitrogen and phosphorous are strongly correlated, probably reflecting common sources (e.g., agricultural and urban runoff). We expect this covariance in Glacier is due to shared patterns in natural sources, such as floodplain upwelling zones (Hauer et al. 2016). In the North Fork of the Flathead (Mills et al. 2011) and many other similar rivers (Biggs et al. 2004), phosphorous is associated with sediment, with higher concentrations reflecting greater sediment loads. This is especially true in high runoff periods where both nutrients and sediment spike (see Schweiger et al. in preparation a). A common way to interpret nutrient concentration in aquatic systems is through their stoichiometry (or the ratio of N to P, i.e., Green and Wang 2008). In Glacier the mean N:P was 28.1, with a minimum of 3.9 and a maximum of 85.1. Ratios below 16 generally indicate possible nitrogen limitation of algal communities (where nutrients are first captured in aquatic food webs). This suggests that on average, phosphorous (as orthophosphate, its biologically available fraction) was often a more limiting nutrient in the park's streams. While complex, excessive concentration of phosphorous is a common cause of eutrophication in freshwater streams

Table 14. Model of total phosphorous (mg/l) in Glacier National Park streams in 2007–2009. Final model selected using Akaike Information Criterion (AIC) and expert opinion from 31 candidate variables. Relative importance (Rel. Imp %) is the total amount of explained variance for each variable expressed as a percentage. Stream order is treated as a factor and all estimates are relative to stream order three (the most common type). *Relative importance value for stream order is for all groups combined.

Model component	Estimate	SE	t	p	Rel. Imp. (%)
Intercept	0.000410	0.01	0.05	0.96	–
Stream order—2	-0.001027	0.00	-0.24	0.81	–
Stream order—3	-0.005361	0.00	-1.42	0.17	–
Stream order—4	-0.008170	0.00	-1.96	0.06	–
Stream order—5	-0.006811	0.01	-1.25	0.22	–
Stream order—6	-0.001553	0.01	-0.16	0.88	–
Stream order—all groups combined	–	–	–	–	0.18*
TSS	0.001152	0.00	4.82	0.00	0.34
Total N	0.036090	0.01	3.47	0.00	0.34
Precipitation, 30 yr	-0.000008	0.00	-2.14	0.04	0.03
Discharge (log)	-0.003967	0.00	-2.09	0.04	0.05
Woody riparian cover	0.006305	0.00	2.36	0.02	0.03
Wood volume	-0.002158	0.00	-1.67	0.11	0.01
Mean substrate diameter	0.005699	0.00	2.05	0.05	0.01

Notes: SE = standard error of coefficient, t = t test value, p = probability of the t. Residual standard error: 0.005 on 34 degrees of freedom, Multiple R^2: 0.83, Adjusted R^2: 0.77, F-statistic: 13.94 on 12 and 34 DF, p-value: 8.204e-10.

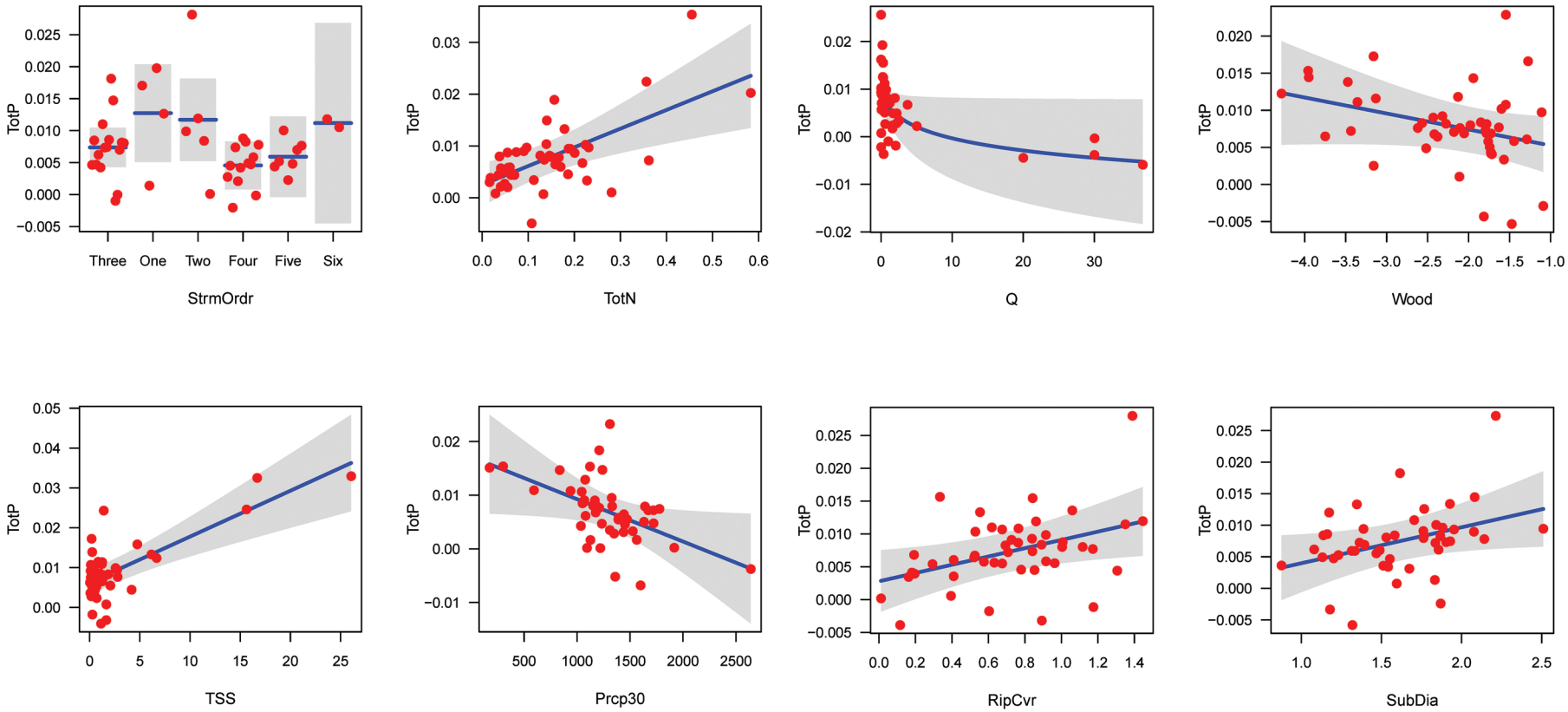


Figure 31. Partial residual plots of an exploratory model of Glacier National Park base flow late summer total phosphorous (mg/l) in 2007–2009. Conditional partial residuals show the relationship between each unique independent variable and total phosphorous, with all other variables held constant at the median for numeric variables and most common level for factors. All variables are shown back transformed to their original scale as applicable. Plots of numeric independent variables include a best fit line and 95% confidence bands around this fit. Box plots of factorial variables include the reference category first or on the leftmost side of the figure, and the 95% confidence interval as the bounding box around the variable's median. Codes in figures are: TotP = total phosphorous (mg/l); StrmOrdr = Strahler stream order; TotN = total nitrogen (mg/l); Q = discharge m3/s (log); Wood = wood volume (m^3/m^2); TSS = total suspended solids (mg/l); Prcp30 = precipitation, 30 year normal in catchment; RipCvr = woody riparian cover (%); SubDia = mean substrate diameter (mm). See the full model results in Appendix F and Table 14.

(Elser et al. 2007). This matches our observation that the park's streams are in general oligotrophic, with little to no eutrophication. Nitrogen and phosphorous concentrations and their stoichiometry do play an important role in the park's streams (i.e., the low concentration of nutrients associated with *Didymosphenia geminata* blooms, see 3.8.4.3 and Schweiger et al. 2011). Moreover, across a variety of spatial scales, levels of nitrogen, and especially phosphorous, remain of concern given recent evidence from Stoddard et al. (2016) that suggests phosphorous is increasing, even in largely undisturbed landscapes such as Glacier.

Of the remaining independent variables in the model, discharge, stream order, and precipitation largely reflect hydrologic controls on nutrient levels (at least indirectly). Given the base flow timing of all our samples, weak negative relationships between these drivers and nutrients likely reflect a dilution effect (greater discharge or precipitation leading to lower concentrations). However, three small stream outliers have exceedingly low flow (and 30 year precipitation normals in their small catchments) yet the highest total phosphorous (and nitrogen) concentrations. One of these sites is immediately adjacent to a road, and high phosphorous may reflect runoff from auto emissions. The other two are located immediately downstream from large wetlands, often important natural sources for high nutrient concentrations (Reddy et al. 1999). As with stream water temperature, we again see a possible link to climate dynamics in an important response in the park's streams. Changes in precipitation have been shown to strongly influence nutrients (i.e., Jeppesen et al. 2009), and documenting this pattern is an ongoing need for network stream monitoring in Glacier.

3.7 Physical habitat

3.7.1 Summary condition

Overall, stream physical habitat in Glacier showed little cause for concern. Streams in a few regions of the park (front country areas below lower Lake MacDonald, Divide Creek near St. Mary, and Railroad Creek near East Glacier) showed some minor sediment issues. Invasive/exotic plants were also found at many sample sites, but again mostly in the front country. Table 15 provides a summary condition of major classes of stream habitat variables monitored during our 2007–2009 survey.

3.7.2 Overview

Here we present results for physical habitat, including important indicators like the amount and type of sediments and riparian vegetation cover for the streams in Glacier. Documenting the status and trends in such attributes is a fundamental part of monitoring streams and they have been used for decades within multiple long-term monitoring programs.

The physical habitat of streams includes stream channel dimensions and patterns (e.g., width and depth, ratio of riffles to pools, gradient, etc.), sediment characteristics (the size and types of sediments make up the streambed and whether the channel is "armored"), amount and type of debris in the stream (including woody debris), and the amount and type of vegetation in the riparian zone and catchment overall. These characteristics are important determinants of the species of plants and animals that live in and near the stream, including diatoms, macroinvertebrates, and fish. Stream physical habitat can be affected by human disturbance. In a near pristine area like Glacier, human disturbances are relatively small (e.g., there are no dams). Nonetheless, Glacier streams may be impacted by development such as roads and trails that can produce excessive sedimentation. Moreover, larger scale or indirect human disturbances such as climate change can change fire frequency and severity, which can increase variability in hydrology, change patterns of wood delivery to channels, and have other effects.

Physical habitat is an important control on ecological processes and biotic condition in Glacier's streams. Habitat attributes vary according to their geomorphic and ecological setting. In particular, stream drainage area and stream gradient are strong natural determinants of many aspects of habitat because of their influence on discharge, flood stage, and stream power (the product of discharge times gradient). Therefore we only consider stream habitat to be a disturbance when it is not in natural equilibrium with the factors that influence it. Anthropogenic activities can alter many aspects of stream habitat – channel dimensions, flood or low flow discharge riparian cover, and especially sediment dynamics. There are generally few direct human disturbances to stream habitat in Glacier. Yet over time complex or indirect disturbances, such as increased sediment loading from more frequent fires or earlier spring runoff and more variable stream flows (such as are predicted with climate change, Goode et al. (2012)), might alter stream habitat in the park.

The SEI protocol adopts a suite of field methods for habitat developed for regional surveys (Fitzpatrick et al. 1998; Stoddard et al. 2005; Heitke et al. 2011) that have been shown to provide a diverse suite of useful data. Most metrics generated from these data are relatively precise and allow meaningful comparisons across large numbers of sites within a region (or a large park like Glacier). However, these methods are

Table 15. Summary condition table for stream physical habitat at Glacier National Park in 2007–2009. We structure the table by indicators of stream ecological integrity. We include the types of assessment points used, a brief description of key results, and symbolize the status and our confidence in these summaries. Key to the condition and confidence symbol: red color = non-reference condition/major disturbance, yellow color = intermediate condition/ moderate disturbance, dark green color = reference condition/minor disturbance, light green color = pristine reference condition/negligible disturbance, no color = unknown or indeterminate; upward arrow = condition is improving, sideways arrows = condition is unchanging, downward arrow = condition is deteriorating, no arrow = unknown trend; heavy border = high confidence, regular border = medium confidence, dashed border = low confidence. Table 5 offers a visual key. For a condensed version of these results, see the summary condition table in the Executive Summary.

Indicator	Condition description	Condition and confidence
Overall stream physical habitat	Overall, the physical habitat of Glacier's streams, rivers, and riparian systems was excellent, with nearly all metrics indicating that the majority of the park's streams were in a minor disturbance class. Front country streams below Lake MacDonald, Divide Creek near St. Mary, and Railroad Creek near East Glacier showed some minor sediment and pool habitat volume issues potentially driven by human disturbance. Invasive/exotic plants were also found at many sample sites, but again mostly in the front country. We have high confidence in our assessment of physical habitat given generally acceptable signal in our indicators and the availability of relevant ecological thresholds and ecoregion baseline assessment points. We are especially confident that our results are useful baselines for understanding changes over time, given the high quality design, data, and modeling we employ.	
Volume	Habitat volume, or the amount of in-channel habitat available to stream biota, is an important determinant of the ecological condition of streams in the park. We use a metric of residual pool depth (measured as the deepest point of a pool relative to the height of the downstream riffle crest) as an important indicator of habitat volume. We developed ecoregional assessment points to help put residual pool depth in the park in context. Results suggest that most streams in Glacier had as much or more habitat volume as reference sites in the surrounding ecoregions. However, more work, especially repeated sampling at SEI sites, is needed to fully interpret these patterns. To better understand the drivers affecting pool depths, we estimated an expected mean pool depth at all Glacier sites using a model developed by the EPA. It predicts mean residual depth from basin area, long-term mean annual precipitation, channel slope, and lithology. We calculated the ratio of observed values in pool depth to their expected score as an ecologically meaningful measure of habitat condition at a site. We then modeled the ratio as a function of select environmental and human disturbance variables, allowing deviations from 1 to be interpreted as possible indications of human disturbance. Almost 20% of the variation in ratios was accounted for by human disturbance (Human Disturbance Index; HDI), with ratios lower with higher HDI. Most sites with low ratios were front country streams, such as Rubideau and Railroad Creeks, and the western tributaries to the North Fork of the Flathead (Coal and Big Creek). The North Fork tributary sites drain watersheds to the west of the park listed by Montana DEQ as not supporting aquatic life due to road construction and use, and streambank modifications/destabilization as a result of forestry in the Smoky Range. Yet other sites (Bowman Lake and Lincoln Creek tributaries) had low ratios (meaning less residual pool depth relative to expectations) and low HDI. These sites are unique in their geomorphic structure and naturally shallow, and they had higher quality ecological integrity. Overall we suspect that streams in the park have not experienced human disturbance that has reduced habitat volumes; however, given our model that isolates HDI as related to select examples of potentially compromised residual pool depths, we suggest future research should be conducted on these patterns. We have high confidence in our assessment given reasonable signal in the data, useful ecoregion baseline assessment points, and robust modelling. We are confident that our results are useful baselines for understanding changes over time, given the high quality design, data, and modeling we employ.	

Table 15 (continued). Summary condition table for stream physical habitat at Glacier National Park in 2007–2009. We structure the table by indicators of stream ecological integrity. We include the types of assessment points used, a brief description of key results, and symbolize the status and our confidence in these summaries. Key to the condition and confidence symbol: red color = non-reference condition/major disturbance, yellow color = intermediate condition/ moderate disturbance, dark green color = reference condition/minor disturbance, light green color = pristine reference condition/negligible disturbance, no color = unknown or indeterminate; upward arrow = condition is improving, sideways arrows = condition is unchanging, downward arrow = condition is deteriorating, no arrow = unknown trend; heavy border = high confidence, regular border = medium confidence, dashed border = low confidence. Table 5 offers a visual key. For a condensed version of these results, see the summary condition table in the Executive Summary.

Indicator	Condition description	Condition and confidence
Complexity	More complex stream habitat generally supports greater ecological integrity and provides for a more intact, higher functioning system. For example, increased complexity in habitat structure usually provides more types of habitat for species of macroinvertebrates, which often is correlated with higher ecological integrity. We focus on three metrics of habitat complexity. We apply ecoregional assessment points and ecological thresholds to help interpret these indicators. Results suggest that most of the streams in Glacier have more complex habitat structure than reference sites in the surrounding ecoregions. Moreover there is sufficient large wood to support properly functioning salmonid habitat in nearly all of the park's streams. We have generally high confidence in our assessment. However, metrics for woody volume and density did have poorer signal to noise ratios and so this should be viewed with some caution. We are confident that our results will be useful baselines for understanding changes over time, given the high quality design, data, and modeling	
Cover	Another key function of stream physical habitat is support of aquatic biota by providing cover for protection from predators or as spawning habitat (among many other functions). Results suggest that most of the streams in Glacier have as much or more cover provided by natural features than reference sites in the surrounding ecoregions. Algal cover is comparable to ecoregional reference sites (note that too much algal cover could be from human-caused nutrient enrichment). Pool density (a measure of the cover of an important habitat feature) was above a bull trout-based threshold in about 70% of the park's streams. This was somewhat surprising given that six of the sites with pool density below the threshold were on the North or Middle Fork of the Flathead, with documented usage by bull trout. Bull trout may use other "non-pool" macro habitat on these rivers and thus this metric may not apply in these systems. We suspect other sites below the threshold are lacking in pools not because of human disturbance but rather due to random variation in channel morphology. We have high confidence in our assessment given useful ecoregion baseline and ecological threshold assessment points. However, cover based metrics had poor signal to noise ratios and these results should be viewed with caution. We are confident that our results are useful baselines for understanding changes over time, given the high quality design, data, and modeling we employ.	
Sediment	Stream substrate size, density, and distribution are major components of in channel and near shore habitat and are some of the most important determinants of overall stream condition. We focus on three core indicators, including percent fines, embeddedness, and relative bed stability. Results suggest that most of the streams in Glacier have sediments comparable to ecoregional reference conditions that should support properly functioning salmonid habitat and not adversely affect key macroinvertebrate species. Our indicator of bed stability measures the tendency of streambed particles to resist transport under a given stream flow. Bed stability is a key component of habitat structure for aquatic organisms. Species are adapted to natural streambed movement – too much or too little can cause stress and lead to reduced ecological integrity. We use ecoregional assessment points to compare bed stability in the park to reference conditions. About 19% of park streams tended towards too much or too little fine sediments. Channels with too much fine sediment can occur in streams with a source of anthropogenic sediment, such as our site on McDonald Creek next to the Going to the Sun Road, as well as in wilderness area with no known human disturbance. We modeled relative bed stability as a function of environmental and human disturbance variables. Controlling for natural drivers, only 3% of the variation in bed stability across all streams was due to human disturbance. Therefore we consider the potential for human caused bed stability issues to be more of something to watch for than a pressing concern for the park's streams in 2007–2009. We have generally high confidence in our assessment given useful ecoregion baseline assessment points and a robust model for the bed stability metric. However, some metrics had poorer signal to noise ratios. We are confident that our results will be useful baselines for understanding changes over time, given the high quality design, data, and modeling we employ.	

Table 15 (continued). Summary condition table for stream physical habitat at Glacier National Park in 2007–2009. We structure the table by indicators of stream ecological integrity. We include the types of assessment points used, a brief description of key results, and symbolize the status and our confidence in these summaries. Key to the condition and confidence symbol: red color = non-reference condition/major disturbance, yellow color = intermediate condition/ moderate disturbance, dark green color = reference condition/minor disturbance, light green color = pristine reference condition/negligible disturbance, no color = unknown or indeterminate; upward arrow = condition is improving, sideways arrows = condition is unchanging, downward arrow = condition is deteriorating, no arrow = unknown trend; heavy border = high confidence, regular border = medium confidence, dashed border = low confidence. Table 5 offers a visual key. For a condensed version of these results, see the summary condition table in the Executive Summary.

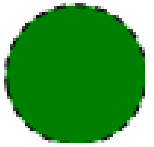
Indicator	Condition description	Condition and confidence
Floodplain interaction	OHabitat features that affect the interaction of a stream with its floodplain are important in determining stream condition. We develop four indicators estimating this: channel sinuosity, bank incision, bankfull width to depth ratio, and bankfull width to wetted width ratio. Comparisons to ecoregional assessment points suggest that most Glacier streams have less incision, lower bankfull width to depth ratios, and lower bankfull width to wetted width ratios than ecoregional reference sites. Overall, conditions in Glacier streams may be more conducive to channel-floodplain interaction than reference sites in the surrounding ecoregions. Less of the park's streams were as sinuous as in surrounding ecoregion reference sites. However, many channels in the park are naturally confined due to steep topography or because they are larger rivers that meander at a scale beyond our sample reach. We suspect that, in general, streams in Glacier have not been subjected to extensive human disturbances that have reduced sinuosity. We have low confidence in our assessment given methodological and scaling issues. Moreover our metrics for sinuosity and incision had poor signal to noise ratios. We are more confident that our results are useful baselines for understanding changes over time, given the high quality design, data, and modeling we employ.	
Hydrologic regime	Hydrologic regime, or the amount and timing of stream flow, and its interaction with other elements of stream habitat are fundamental components and determinants of the condition of streams. We measure instantaneous stream flow with every full sample event and harvest continuous discharge data from any nearby USGS or other stream gauge where available. We present trend models of these continuous data in the Glacier SEI sentinel site report (Schweiger et al. in preparation a). We also use two general metrics derived from habitat data as indirect indicators of hydrologic regime: the ratio of base summer flow to annual mean runoff as an index of "droughtiness," and the ratio of bankfull depth to wetted depth as a morphometric index of "flashiness." About 70% of the park's streams had minor levels of disturbance to their hydrologic regimes from droughtiness (as indicated by the ratio of base summer flow to annual mean runoff), suggesting that drought risk is lower in most of the park's streams than in surrounding ecoregion reference sites. This is expected given the park's high elevation, high levels of precipitation, and minimal human modification (i.e., water diversion) that often increase drought risk. Likewise about 60% of the stream length in the park was less flashy (as indicated by the ratio of bankfull depth to wetted depth) than ecoregional reference sites. High flows with dramatic flooding can certainly happen in the park, but sites that tend to do this do not have any meaningful human disturbance that might cause this flashiness. Rather this likely reflects large watersheds that store large volumes of water that can be released in high flows. We have medium confidence in our assessment given some important assumptions and the coarse nature of the habitat based hydrologic metrics. Moreover the droughtiness metric had a poor signal to noise ratio. We are more confident that our results are useful baselines for understanding changes over time, given the high quality design, data, and modeling we employ. *Of note, about 13% of the park's streams with higher droughtiness (or in a major stress class) may be something to watch as climate change proceeds and the park's namesake glaciers disappear. For example, if combined with lower base flow habitat volume, higher water temperatures, and less glacial snow/ice melting in later summer, the impacts to stream biota from drought might be accentuated.*	

Table 15 (continued). Summary condition table for stream physical habitat at Glacier National Park in 2007–2009. We structure the table by indicators of stream ecological integrity. We include the types of assessment points used, a brief description of key results, and symbolize the status and our confidence in these summaries. Key to the condition and confidence symbol: red color = non-reference condition/major disturbance, yellow color = intermediate condition/ moderate disturbance, dark green color = reference condition/minor disturbance, light green color = pristine reference condition/negligible disturbance, no color = unknown or indeterminate; upward arrow = condition is improving, sideways arrows = condition is unchanging, downward arrow = condition is deteriorating, no arrow = unknown trend; heavy border = high confidence, regular border = medium confidence, dashed border = low confidence. Table 5 offers a visual key. For a condensed version of these results, see the summary condition table in the Executive Summary.

Indicator	Condition description	Condition and confidence
Riparian vegetation	Riparian vegetation has many important relationships with channel structure, cover, shading, nutrient inputs, large woody debris, and wildlife corridors. It also acts as a buffer against anthropogenic disturbance. We use three core metrics focused on different aspects of riparian vegetation cover. Results suggest that much of the stream length in Glacier has high levels of riparian cover relative to ecoregional reference sites. Sites that lack cover do so largely due to natural patterns (i.e., they are in the alpine or are large rivers with extensive nonvegetated lateral bars). We generally have high confidence in our assessment given generally acceptable signal in the data and relevant ecoregion baseline assessment points. We are especially confident that our results are useful baselines for understanding changes over time, given the high quality design, data, and modeling we employ.	
Invasive/exotic plants	Understanding and monitoring invasive/exotic taxa in riparian systems is key for park resource management. Invasive/exotic riparian taxa have been associated with multiple negative effects, including 1) alteration of fire, nutrient, or hydrologic regimes; 2) excess carbon sequestration; and 3) changes to plant and animal distributions. An invasive/exotic species list was developed with Glacier staff. The list includes 15 taxa that are ecologically varied, easy to identify, truly invasive, and ecologically or economically intrusive. We also estimate an assemblage level Invasive Plant Index that combines all taxa into a single indicator of the invasion level at a site. We develop a meaningful ecological threshold-based assessment point for this index by assuming that a negligible stress assessment point occurs where there are no (zero) occurrences of any invasive/exotic taxa. This assumes that the reference state is for none of these species to be present at all. This is in keeping with the NPS approach to managing invasive/exotic plants. Spotted knapweed (Centaurea maculosa) and Canada thistle (Cirsium arvense) were the most commonly recorded taxa, occurring with an average frequency of 0.08 and 0.06, respectively. Maximum values occurred at Railroad Creek tributary and Divide Creek, both of which are on the park's boundary and near roads. Around 62% of the park's stream length was weed free or in a negligible stress class. Population scale inference requires use of only survey sites; therefore, gradient sites, often chosen because of known weed infestations, are not included in this and our estimate of weed free stream may be small. We generally have high confidence in our assessment given generally acceptable signal in the data and meaningful ecological threshold assessment points. We are especially confident that our results are useful baselines for understanding changes over time, given the high quality design and data. *Note: we documented simple presence/absence of 15 invasive/exotic species and our survey design does not target stream sites with high invasion probabilities. Therefore, this assessment should be used to understand long-term status of invasive aquatic plants across riparian areas of Glacier and not as a management tool (e.g., to identify potential treatment areas or invasion "hot spots").*	

not equivalent to an engineering grade survey of physical attributes for a specific stream site; therefore, our results are not meant to be evaluated at the single site scale (e.g., to determine the effectiveness of a restoration effort at a specific stream reach). While many of our habitat metrics are synthetic, we do not develop a comprehensive multimetric index for habitat. Al-Chokhachy et al. (2010) present methods for doing this, which we may explore in the future.

To assess our physical habitat results, we follow the hierarchy given in the assessment section 2.4.4.2, above, with any details specific to habitat metrics clarified in Appendix D.

3.7.3 Physical habitat: detailed results and interpretation

The physical habitat results presented here are based on 2007–2009 survey site events (Table 16). We include both population level results and select site level results. In addition, we develop select models that are relevant at the site scale. Results focused on patterns over time (change and trend) in select physical habitat metrics are presented in our sentinel site report (Schweiger et al. in preparation a).

We base our selection of 22 "core" metrics on Stoddard et al. (2005) and Kaufmann (1993). The SEI database includes dozens of additional habitat metrics (available upon request from the network). The core attributes fall within seven general categories of physical habitat condition. These 22 attributes are considered essential for evaluating physical habitat in larger scale monitoring and assessment, and are incorporated in many other habitat survey protocols (e.g., Platts et al. 1983; Lazorchak et al. 1998; Fitzpatrick et al. 1998; Angradi et al. 2006; Kusnierz et al. 2013).

3.7.3.1 Habitat volume

Habitat volume, or the amount of in channel habitat available to stream biota, is an important determinant of the condition of streams in the park. The size of a stream is a function of its drainage area and discharge (which are relatively immutable); however, anthropogenic activities can alter channel dimensions and flood or low flow discharge – all of which can alter the quantity and quality of aquatic habitat. While there are few direct human disturbances to stream habitat volume in Glacier, over time, complex or indirect disturbances such as increased sediment loading from more frequent fires or earlier spring runoff and more variable stream flows (such as are predicted with climate change, Goode et al. (2012)) might alter stream habitat volume. We develop a model of habitat volume in section 3.7.4, below, that connects this important response in the park's streams to natural and human drivers.

SEI habitat data can be used to estimate simple metrics of habitat volume such as mean width or depth. While useful, these metrics are sensitive to daily variation in stream flow and may not necessarily reflect habitat volume during limiting drought conditions. Therefore, as a more informative indicator of habitat volume, we used a residual pool depth metric (hereafter, pool depth) that accounts for stream flow (Stack and Beschta 1989; Kaufmann et al. 1999). This metric is independent of instantaneous discharge as it is based on the profile of the stream bottom along its deepest point (regardless of how much water is in the channel). Reach-wide pool depth varies widely across streams, so we log transformed values. As logged values of residual mean depth approach and fall below zero, there is less habitat volume available for stream biota.

Around 17% of the park's streams had residual volumes below a major disturbance assessment point of 0.08 (~1 cm), while around 63% had volumes above a minor stress level of 0.6 (~5 cm). The balance of about 20% of the park's streams were in a moderate disturbance class with residual volumes between these two assessment points. The median log residual depth in Glacier was 0.7 (or about 5 cm), with a maximum around 1.6 (~42 cm) recorded in a Belly River site. We feel the higher percentage in a major disturbance class reflects the large number of smaller streams included in the survey (given their dominance of the stream types in the park) with relatively "shallow" channel profiles. We do not believe that streams in Glacier have been subjected to extensive human disturbances that have reduced habitat volume.

Signal : noise

The S:N of habitat volume was acceptable and generally comparable with EMAP results. The high value suggests that the metric is estimating Glacier stream habitat volumes with acceptable precision and indicates that our measure of habitat volume is likely less influenced by daily varying stream flow.

3.7.3.2 Habitat complexity

More complex stream habitat should generally support greater ecological integrity and provide for a more intact, higher functioning system (Gorman and Karr 1978; Benson and Magnuson 1992). SEI monitoring in Glacier provides several metrics that estimate this important attribute of streams (Kaufmann 1993; Stoddard et al. 2005). We selected three to interpret here: 1) coefficient of variation in thalweg depth, 2) the volume of all wood, and 3) the density of large wood.

Table 16. Summary of 22 core physical habitat metrics in the streams of Glacier National Park, 2007–2009.

Category	Habitat indicator	Change with decrease in ecol. condition	Min. value from survey sites (all sites)	Park scale median	Max. value from survey sites (all sites)	LCL	UCL	Assessment points		Assess. point type	% of park streams in stressor class			Signal to Noise ratio (S:N)	EMAP Signal to Noise ratio (S:N)
								Major	Minor		Major	Moderate	Minor		
Habitat volume	Residual pool depth (m, log)	Dcr	-0.31	0.7	1.63	0.55	0.86	<0.08	>0.6	ERG	16.7	20.4	62.9	4.4	10.9
Habitat complexity	Coefficient of variation in thalweg depth	Dcr	0.19	0.4	0.99	0.38	0.54	<0.2	>0.3	ERG	4.6	8.6	86.8	4.8	7.4
	Volume of woody debris (m^3/m^2)	Dcr	0	0.01	0.08	0.007	0.018	<0.0	>0.003	ERG	1.1	13.6	85.3	0.1	2.4
	Density of large wood (number /100 m)	Dcr	0	18.6	57.91	10.4	34.6	–	>1.2[1]	THR	–	–	96.3	0.9	4.6
Cover for stream biota	Areal cover of filamentous algae (proportion)	Inc/Dcr	0	0.002	0.22	0	0.18	–	–	–	–	–	–	0.1	5.5
	Areal cover of all natural features (proportion)	Dcr	0.1	0.45	1.25	0.37	0.68	<0.12	>0.27	ERG	9.5	6.8	83.7	0.9	2.1
	Pool density (m of pool per m of sampled stream)	Dcr	0.003	0.04	0.12	0.03	0.08	–	>0.03m[1]	THR	–	–	69.8	8.2	–

Notes: Median and confidence intervals are derived from survey-design based estimation methods. Minimum and maximum values are at the site scale and (if meaningfully different) given for survey only sites and (in parentheses) all sites. Codes for assessment point types are: THR = ecological threshold and ERG = ecoregional. Numbered table notes provide additional details on each type of assessment point. For ERG assessment points and responses that increase with decreasing condition, we use the >95th percentile for major disturbance. We use a <75th percentile for minor disturbances. For responses that decrease with decreasing condition, we use the <5th percentile for major disturbance and >25th percentile values for minor disturbances (stressors) or a reference condition. A moderate disturbance class falls in between these values. Note that where there is only one assessment point there is no moderate class and we therefore lump moderate and minor categories together and use the color code from the minor class. The percentage of Glacier National Park streams in major/moderate/minor stressor classes were derived by comparing design-based results to assessment points. Some percentages are approximate as assessment points often fell between two values in the cumulative distribution and must therefore be interpolated. S:N was derived across all 49 sites and the 97 visits to these sites from 2007 to 2009. Problematic S:N values are below 1.0. EMAP S:N estimates are from Stoddard et al. (2005).

[1] Ecological threshold from USFWS (1998) for "Functioning Appropriately" bull trout populations; wood and pool density values are scaled to a mean sampled reach length and width at Glacier National Park of 500m;

[2 a/b] Ecological threshold from Bryce et al. (2010); a) Salvelinus confluentus and Oncorhynchus clarkii; b) eight sediment sensitive macroinvertebrate taxa that occur in or around Glacier National Park.

[3] Assessment point values for relative bed stability are given for armoring, assuming an increase with decreasing condition (>95th and <75th), and for fining, assuming a decrease with decreasing condition (<5th >25th); see text and Figure 38.

* Incision results based on a very small sample of only six sites given methodological errors in 2007 and 2008; use with caution.

** Design-based mean and its lower and upper 95% confidence interval limits.

Table 16 (continued). Summary of 22 core physical habitat metrics in the streams of Glacier National Park, 2007–2009.

Category	Habitat indicator	Change with decrease in ecol. condition	Min. value from survey sites (all sites)	Park scale median	Max. value from survey sites (all sites)	LCL	UCL	Assessment points		Assess. point type	% of park streams in stressor class			Signal to Noise ratio (S:N)	EMAP Signal to Noise ratio (S:N)
								Major	Minor		Major	Moderate	Minor		
Sediment	Streambed silt and finer (<0.6 mm) (%)	Inc	0	1.9	58.06	1.3	3.0	–	<5[2a] <3[2b]	THR	–	–	73.2[2a] 67.2[2b]	0.4	22.2
	Streambed sand and finer (<2 mm)(%)	Inc	0	3.9	63.87	2.7	14.2	–	<13[2a] <10[2b]	THR	–	–	66.2[2a] 63.4[2b]	3.9	18.3
	Substrate embedded by sand and fines (wadeable streams only) (%)	Inc	0	19.0	73.0	16.15	22.9	–	<20[1]	THR	–	–	55.1	2.7	13.8
	Relative bed stability - mean bed particle diameter / critical mobile diameter at bankfull (index, log)	[3]Armoring: Inc [3]Fining: Dcr	-2.39	-0.63	0.7	-0.88	-0.4	[3]A: >0.4 [3]F: <-1.7	[3]A:<-0.4 [3]F: >-1.1	ERG	[3]A:2.0 [3]F:13.5	[3]A: 2.5 [3]F: 4.9	[3]A: 75.5 [3]F: 81.6	1.6	8.7
Floodplain interatcion	Channel sinuosity (index, log)	Dcr	0.002	0.04	0.53	0.03	0.07	<0.005	>0.03	ERG	17.2	4.8	57.8	0.5	4.3
	*Incision from terrace to bankfull ht. (m)	Inc	*0	*0.47	*0.74	*0	*0.71	>3.0	<0.8	ERG	*0	*0	*100	*0.01	3.9
	Bankfull width/depth ratio (m, log)	Inc	0.58	0.88	2.09	0.82	1.11	>1.8	<1.3	ERG	8.9	6.3	84.8	16.7	6.0
	Bankfull width / wetted width (flood inundation potential) (m, log)	Dcr	0.03	0.13	0.79	0.11	0.24	<0.03	>0.09	ERG	2.1	21.6	76.3	1.6	6.9

Notes: Median and confidence intervals are derived from survey-design based estimation methods. Minimum and maximum values are at the site scale and (if meaningfully different) given for survey only sites and (in parentheses) all sites. Codes for assessment point types are: THR = ecological threshold and ERG = ecoregional. Numbered table notes provide additional details on each type of assessment point. For ERG assessment points and responses that increase with decreasing condition, we use the >95th percentile for major disturbance. We use a <75th percentile for minor disturbances. For responses that decrease with decreasing condition, we use the <5th percentile for major disturbance and >25th percentile values for minor disturbances (stressors) or a reference condition. A moderate disturbance class falls in between these values. Note that where there is only one assessment point there is no moderate class and we therefore lump moderate and minor categories together and use the color code from the minor class. The percentage of Glacier National Park streams in major/moderate/minor stressor classes were derived by comparing design-based results to assessment points. Some percentages are approximate as assessment points often fell between two values in the cumulative distribution and must therefore be interpolated. S:N was derived across all 49 sites and the 97 visits to these sites from 2007 to 2009. Problematic S:N values are below 1.0. EMAP S:N estimates are from Stoddard et al. (2005).

[1] Ecological threshold from USFWS (1998) for "Functioning Appropriately" bull trout populations; wood and pool density values are scaled to a mean sampled reach length and width at Glacier National Park of 500m;

[2 a/b] Ecological threshold from Bryce et al. (2010); a) Salvelinus confluentus and Oncorhynchus clarkii; b) eight sediment sensitive macroinvertebrate taxa that occur in or around Glacier National Park.

[3] Assessment point values for relative bed stability are given for armoring, assuming an increase with decreasing condition (>95th and <75th), and for fining, assuming a decrease with decreasing condition (<5th >25th); see text and Figure 38.

* Incision results based on a very small sample of only six sites given methodological errors in 2007 and 2008; use with caution.

** Design-based mean and its lower and upper 95% confidence interval limits.

Table 16 (continued). Summary of 22 core physical habitat metrics in the streams of Glacier National Park, 2007–2009.

Category	Habitat indicator	Change with decrease in ecol. condition	Min. value from survey sites (all sites)	Park scale median	Max. value from survey sites (all sites)	LCL	UCL	Assessment points		Assess. point type	% of park streams in stressor class			Signal to Noise ratio (S:N)	EMAP Signal to Noise ratio (S:N)
								Major	Minor		Major	Moderate	Minor		
Hydrologic regime (instantaneous stream flow and habitat based indicators)	Instantaneous discharge (m^3/s)	Inc/Dcr	0.0002	0.29	36.81	0.05	0.32	–	–	–	–	–	–	2.5	–
	Base summer (low) flow /annual mean runoff (inverse index of "droughtiness") (index, log)	Dcr	-3.56	-2.1	-1.05	-2.2	-1.79	<-2.7	>-2.2	ERG	13.9	16.8	69.3	0.3	0.8
	Bankfull height / wetted depth (morphometric index of "flashiness") (index, log)	Inc	0.07	0.44	2.22	0.31	0.66	>2.1	<0.6	ERG	0.8	39.4	59.8	29.1	4.7
Riparian vegetation cover	Stream bank vegetation cover (%)	Dcr	2.9	58.9	89.84	39.7	63.8	<5.6	>16.8	ERG	10.1	4.6	85.3	1.6	34.8
	Riparian canopy+mid+ground layer total vegetation cover (proportion)	Dcr	0.41 (0.21)	1.1	2.33	0.81	1.48	<0.5	>0.9	ERG	4.5	36.4	59.1	1.9	3.8
	Riparian canopy +mid+ground layer total woody vegetation cover (proportion)	Dcr	0.01	0.68	1.45	0.61	0.92	<0.2	>0.6	ERG	8.5	21.2	70.3	2.5	8.0
	Frequency of invasive/ exotic plants	Inc	0	0 0.23**	1.73 (2.0)	0 0.10**	0.07 0.37**	Negligible = 0	–	THR		38.1	Negligible (61.9)	1.2	–

Notes: Median and confidence intervals are derived from survey-design based estimation methods. Minimum and maximum values are at the site scale and (if meaningfully different) given for survey only sites and (in parentheses) all sites. Codes for assessment point types are: THR = ecological threshold and ERG = ecoregional. Numbered table notes provide additional details on each type of assessment point. For ERG assessment points and responses that increase with decreasing condition, we use the >95th percentile for major disturbance. We use a <75th percentile for minor disturbances. For responses that decrease with decreasing condition, we use the <5th percentile for major disturbance and >25th percentile values for minor disturbances (stressors) or a reference condition. A moderate disturbance class falls in between these values. Note that where there is only one assessment point there is no moderate class and we therefore lump moderate and minor categories together and use the color code from the minor class. The percentage of Glacier National Park streams in major/moderate/minor stressor classes were derived by comparing design-based results to assessment points. Some percentages are approximate as assessment points often fell between two values in the cumulative distribution and must therefore be interpolated. S:N was derived across all 49 sites and the 97 visits to these sites from 2007 to 2009. Problematic S:N values are below 1.0. EMAP S:N estimates are from Stoddard et al. (2005).

[1] Ecological threshold from USFWS (1998) for "Functioning Appropriately" bull trout populations; wood and pool density values are scaled to a mean sampled reach length and width at Glacier National Park of 500m;

[2 a/b] Ecological threshold from Bryce et al. (2010); a) Salvelinus confluentus and Oncorhynchus clarkii; b) eight sediment sensitive macroinvertebrate taxa that occur in or around Glacier National Park.

[3] Assessment point values for relative bed stability are given for armoring, assuming an increase with decreasing condition (>95th and <75th), and for fining, assuming a decrease with decreasing condition (<5th >25th); see text and Figure 38.

* Incision results based on a very small sample of only six sites given methodological errors in 2007 and 2008; use with caution.

** Design-based mean and its lower and upper 95% confidence interval limits.

Coefficient of variation in thalweg

The coefficient of variation in thalweg (where thalweg refers to the part of the channel with the most flow, usually the deepest location on a cross section) depth directly measures how variable (or complex) the bottom of a stream is. Higher values (the range is 0 to 1.0) suggest greater dispersion among replicates of thalweg depth (or a more complex channel profile). The median thalweg profile coefficient of variation in Glacier was 0.4 (Table 16). Around 87% of the stream in Glacier was above a minor disturbance level of 0.3, with only about 5% below or more homogenous than the major disturbance level of 0.2. This suggests that most of the stream in the park had complex patterns in depths. Our site on a tributary to Bowman Lake had one of the highest values – visually evident in its classic step-pool structure (Figure 32).

Woody debris

Woody debris is one of the most important sources of structure (or complexity) in most stream types (Harmon et al. 1986; Robison and Beschta 1989; Gurnell et al. 2002). We used two woody debris metrics as estimates of the contribution of wood in the channel to habitat complexity: 1) the volume of woody debris per m^2 of bankfull channel, which incorporates both the frequency and amount of wood of any size, and 2) the density of large wood (>0.3 m in diameter and >5 m in length). Large wood is critical (i.e., Fausch and Northcote 1992), but smaller pieces, especially when they add up to more total volume, are also important, particularly in smaller channels (Lester et al. 2007).

The median volume of woody debris in Glacier (Table 16) was 0.01 m^3/m^2 of bankfull channel area. While this may seem like a low number, it is greater than around 86% of reference caliber streams in the park's ecoregions (with a minor disturbance level of 0.003 m^3/m^2). Only around 1% of the park's streams were below the major disturbance level of 0 m^3/m^2. This is not surprising given the lack of any current and very little historical forestry in catchments that are inter-



Figure 32. Field crew collecting data from a small, steep step-pool structured tributary to Bowman Lake in 2008, Glacier National Park. The area in the photo shows good examples of complex habitat, with extensive variation in stream depths, cobble and boulder substrates, and heavy riparian cover. (NPS/BILLY SCHWEIGER)

nal to the park and higher rates of delivery of woody debris into streams from productive watersheds and high gradient streams.

Finally, we apply an ecological threshold developed for bull trout habitat assessments by USFWS (1998) to the density of large (>0.3 m in diameter and >5 m in length) wood per 100 meters of stream. This threshold defines habitat conditions suggested for a properly functioning fishery. It also assumes that there are adequate sources of woody debris available for both long- and short-term recruitment (which the park should readily meet). The median density of larger woody debris was 18.6 per 100 m of stream in Glacier (Table 16). The maximum value was 57.9 pieces of large wood per 100 m of channel (recorded in Appistoki Creek). Over 96% of the streams in the park had more wood than this threshold. This suggests that there is enough habitat complexity provided by large wood to support viable bull trout populations in most of the park's streams (Figure 33; clearly many other attributes are required for a functional bull trout fishery, i.e., Muhlfeld and Marotz 2005). Figure 34 shows dense, large, woody debris typical of many streams in the park.

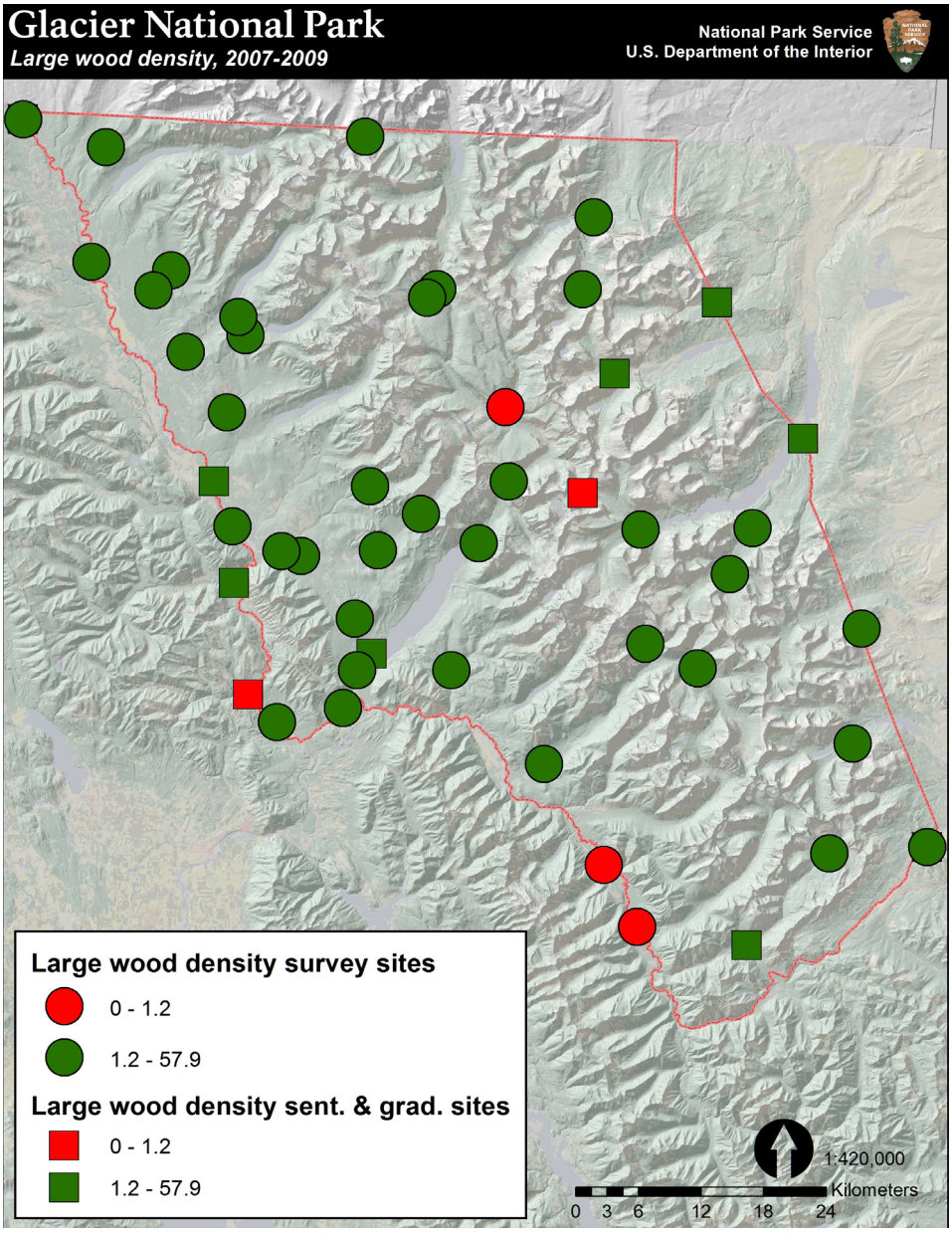


Figure 33. Map of large wood density at Stream Ecological Integrity survey sites and sentinel (sent.) and gradient (grad.) sites in Glacier National Park, 2007–2009. The two colored condition classes are based on assessment points from USFWS (1998). Red indicates sites with wood below the amount suggested for properly functioning bull trout habitat. See Appendix A for a complete list of site numbers and names.



Figure 34. Field crews collect data on stream physical habitat on Quartz Creek, 2008, Glacier National Park. The photo shows a good example of dense, large, woody debris typical of many streams in the park. (NPS/BILLY SCHWEIGER)

Signal : noise habitat complexity metrics

The S:N ratios of the habitat complexity metrics were mixed. Thalweg depth variation was high but the two woody debris metrics were low, especially the volume across all size classes. It is more difficult to count all wood versus just large wood, and smaller wood is more readily moved from the channel by variable stream flow. Similar patterns were seen in the EMAP S:N values. This suggests that these metrics may have mixed capacity to estimate stream habitat complexity in Glacier with acceptable precision.

3.7.3.3 Cover for stream biota

Another key function of stream physical habitat is support of aquatic biota through cover (i.e., for protection from predators or as spawning habitat, etc.). While many of the habitat metrics we interpret in this report are related to this function, following Stoddard et al. (2005), Hankin and Reeves (1988), and Kaufmann and Whittier (1997), we interpret three metrics of in channel cover as important estimates of the amount of cover provided for stream biota. These include: 1) the cover of filamentous algae, 3) the combined cover of all natural features (large wood, brush, overhanging vegetation, live trees and roots, boulders, rock ledges, and undercut banks) in the channel or on its banks, and 3) pool density.

Filamentous algae

The cover of filamentous algae may have a more complex relationship with human disturbance in Glacier. In other systems (i.e., the Clark Fork River in Grant-Kohrs Ranch National Historic Site; see Schweiger et al. 2014a) cover from algae can be excessive and a negative factor in stream ecological integrity, with too much cover suggesting anthropogenic eutrophication issues. This is not typical in Glacier, where algal mats can provide important refugia for fish fry and other biota and play an important role as the base of the

food web (see Figure 29), even at relatively high coverages (Dudley et al. 1986). Yet in the extreme, or where there is a clear connection to a local anthropogenic nutrient source, the cover of filamentous algae is likely a stressor to stream condition. Given this uncertainty, we do not develop ecoregional assessment points for algal cover. We still include the data as a core metric here with the expectation that more research might clarify the pattern. For our third metric, pool density, given a well-documented link with salmonids (i.e., Muhlfeld and Bennett 2001; Harper and Farag 2004) and a strong link to land management practices (Lisle and Hilton 1991; Kershner et al. 2004), we use an ecological threshold from USFWS (1998) that sets a required pool density for properly functioning bull trout habitat.

The median filamentous algal cover in Glacier was 0.2% (Table 16). As noted we do not further assess these results here. Suplee et al. (2008) suggests that in the Northwestern Glaciated Plains ecoregion (the Hi-line region of the state east of Glacier), streambed cover by filamentous algae should generally be less than 30% for a single sampling event and less than 25% for a summertime average. This suggests that the typical cover in Glacier in 2007–2009 was likely not problematic, but more data are needed.

Combined cover of all natural features

The median cover in Glacier from all in channel natural features was 45% (Table 16). Around 84% of the stream in Glacier was above a minor disturbance level of 27%, with only about 10% was below the major disturbance cover level of 12%. This suggests that most of the stream in the park had more extensive cover of natural features than reference sites in the park's ecoregions. A site on Dutch Creek is a good example of a stream with a high proportional coverage of natural features (Figure 35). Conversely, Divide Creek (see Figure 46) shows one of the few sites in the park with very little cover from natural features.

Pool density

About 70% of the stream in the park had pool density above an ecological threshold of approximately 0.03 meters of pool length per meter of stream as used to assess bull trout habitat suitability by the USFWS (1998). We rescaled the original USFWS threshold to the mean wetted width of 13 m and sampled reach length of 520 m for SEI sites (it is also converted from pools per mile in the USFWS formulation). The USFWS bull trout threshold does not specify the stream flow at which pools are to be quantified or when in the water year they are to be assessed, but it is probably at base flow



Figure 35. High natural feature cover on Dutch Creek, 2008, Glacier National Park. See Figure 46 for an example of a (rare) stream in the park with low natural feature cover. (NPS/BILLY SCHWEIGER)

(when we sample) when salmonids are likely most stressed. That 30% of the park's streams are below this threshold is somewhat surprising. Six of the sites with pool density below the threshold were on the North or Middle Fork of the Flathead (Figure 36). While our scaling of the USFWS threshold ideally adjusts our use of this value as an assessment point to these larger rivers in the park, this is approximate and may not quite work for these larger rivers where pools are not as common naturally. Furthermore there is documented use of these two rivers by bull trout (Fraley and Shepard 1989; Muhlfeld and Marotz 2005). This research suggests that pool habitat used by bull trout may be augmented by deep runs (habitat with the depth of pools but faster flowing water). We suspect that some of the other sites below the pool threshold are not viable bull trout habitat in other respects (e.g., our site on the Rubideau Creek tributary is not bull trout habitat for many other reasons). Moreover we do not suspect that these sites are lacking in pools because of human disturbances but rather due to random variations in habitat structure, especially channel morphology.

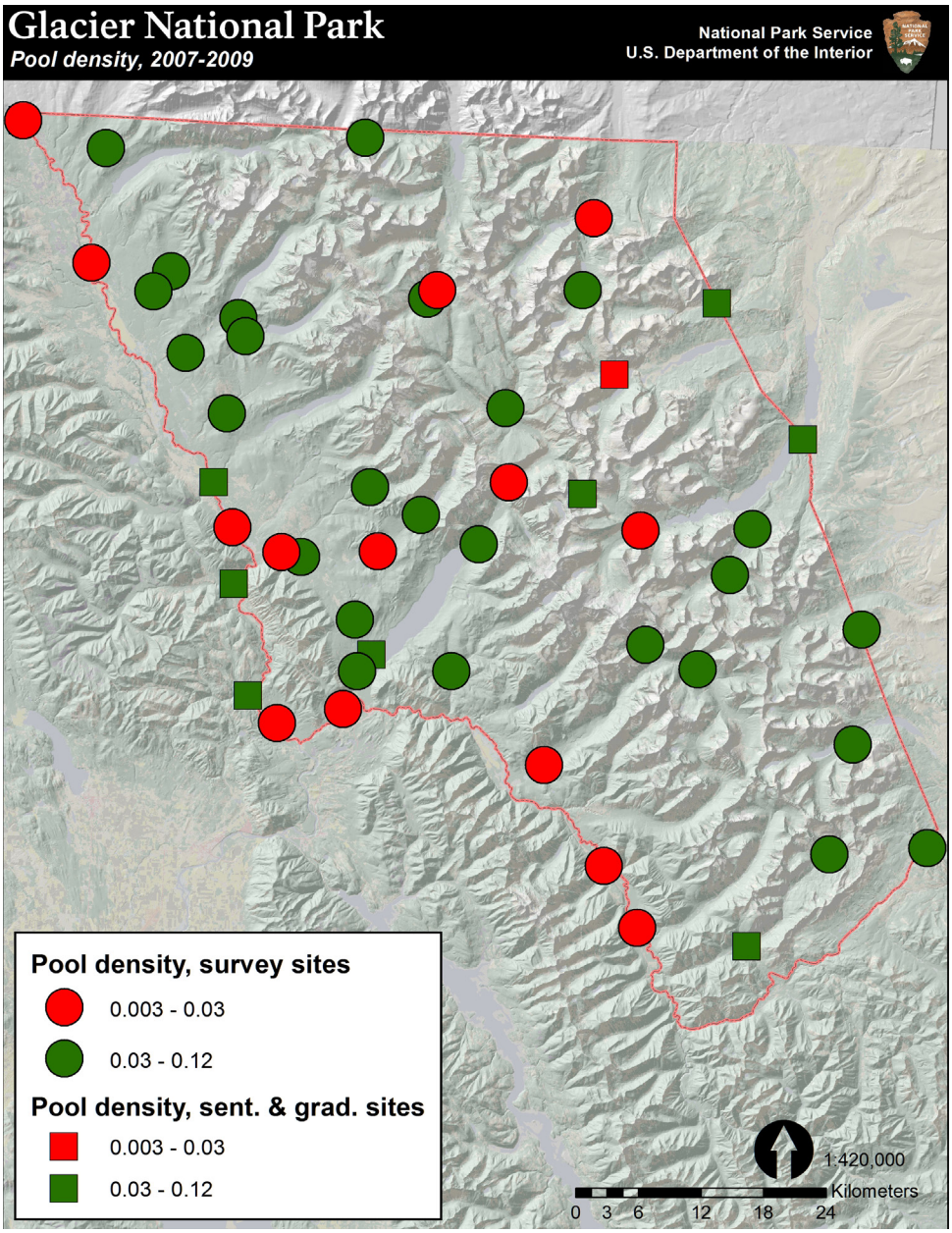


Figure 36. Map of pool density at Stream Ecological Integrity survey sites and sentinel (sent.) and gradient (grad.) sites in Glacier National Park, 2007–2009. The two colored condition classes are based on bull trout assessment points from USFWS (1998). Red indicates sites with pool density below the amount suggested for properly functioning bull trout habitat. See Appendix A for a complete list of site numbers and names.

Signal : noise
The S:N of the cover for stream biota metrics was variable, with low values for algae and natural cover and a high value for residual pool density. Thus these metrics may have mixed capacity to estimate conditions in Glacier with acceptable precision. Cover (especially from algae) can vary over time naturally and can be hard to safely estimate with precision in challenging stream habitats.

3.7.3.4 Sediment

Stream substrate size, density, and distribution are major components of in channel and near shore habitat and can be important determinants of overall stream condition. Along with bedform, substrate size influences hydraulic roughness, water velocity, and the interstices amongst substrate particles that provide habitat for macroinvertebrates and smaller vertebrates. The size of substrates and their relative extents on streambeds are often sensitive indicators of the effects of human activities on streams (MacDonald et al. 1991; Barbour et al. 1999). Accumulations of fine substrate particles can fill interstitial spaces and reduce habitat for benthic fish, macroinvertebrates, and diatoms (Platts et al. 1983; Hawkins et al. 1983; Rinne 1988; Yamada and Nakamura 2002; Suttle et al. 2004). In addition, fines impede circulation of oxygenated water into hyporheic habitats. Decreases in particle size and increases in streambed fine sediments can destabilize stream channels (Wilcock 1997, 1998) and may indicate increases in the rates of upland erosion and sediment supply from anthropogenic disturbances (Lisle 1982; Dietrich et al. 1989; Waters 1995). Because of these and other important aspects of stream substrate, we include three substrate focused metrics following Stoddard et al. (2005), and Kaufmann et al. (1999): 1) percent silt and finer (also often called "fines"), 2) percent sand and finer, and 3) percent embeddedness.

Relevant ecological thresholds are available for all three of the substrate metrics (Table 16). Bryce et al. (2010) define thresholds for silts and finer and sand using bull and cutthroat trout habitat and a suite of eight macroinvertebrate taxa that also occur in the park or its ecoregions. They provide mean "optimum tolerance" percent sediment cover thresholds that protect and maintain self-sustaining populations of these native sediment-sensitive aquatic species. The best available threshold for embeddedness is from USFWS (1998); it sets the maximum percentage of larger substrates surrounded by sands and fines (embeddedness) at 20% in properly functioning bull trout rearing habitat.

Percent silt and finer and percent sand and finer
The median percent silt and finer in Glacier was 1.9. About 73% and 67% of Glacier streams were below this value or in a minor disturbance state for vertebrates (salmonids) and invertebrates, respectively (Figure 37). The median percent sand and finer in Glacier was 3.9. About 66% and 63% of Glacier streams were below this value or in a minor disturbance state for vertebrates and invertebrates, respectively. These two metrics reflect the dominant larger substrate types in most Glacier streams and the largely in-balance sediment dynamics typical of the unmodified channels in the park. Note that these sediment results generally match results from macroinvertebrate and diatom metrics that assay sediment impacts as presented below in section 3.8.

The median embeddedness in Glacier was 19% (Table 16). About 54% of Glacier streams were below this value or in a minor disturbance state. It is unclear why this metric would suggest less of the park was in a minor disturbance state than the percent fines and sand metrics. There was a high degree of natural variability in embeddedness, with few sites having extreme values (the maximum was 73%, see Figure 25). Embeddedness was not collected from non-wadeable sites due to safety concerns. The thalweg of these rivers would generally have little to no embedded substrates, so there may be some unaccounted bias towards smaller streams with the higher embeddedness values. However this is most likely due to the different sources for these ecological thresholds. The Bryce et al. (2010) percent fines and sand values are more reliable as they are based on recent research and include macroinvertebrates that interact with substrates throughout their entire life cycle (versus the salmonids where this is primarily during rearing). The USFWS (1998) embeddedness threshold is also quite conservative relative to a minor disturbance threshold (an embeddedness value of 41%) in the park's ecoregion reference sites.

Relative bed stability
An additional important and unique metric we use to characterize substrates in Glacier is relative bed stability (RBS). RBS measures the tendency of streambed particles to resist transport under a given stream flow. We use an RBS metric developed in Kaufmann et al. (1999, 2006, 2008, 2009) and employed by our collaborators at a broad diversity of stream monitoring sites across the state and region. In summary, the metric compares the measured median substrate size in a streambed to the maximum theoretical substrate size carried during bankfull flow conditions. This ratio then estimates the deviation from what a site "should" have under minimal stress or reference conditions. The ratio can indicate a site either has too many fine sediments or too many coarse sediments. For example, if a stream is capable of moving large boulders during bankfull flow events, yet the measured median substrate is fines and silts, a RBS metric would

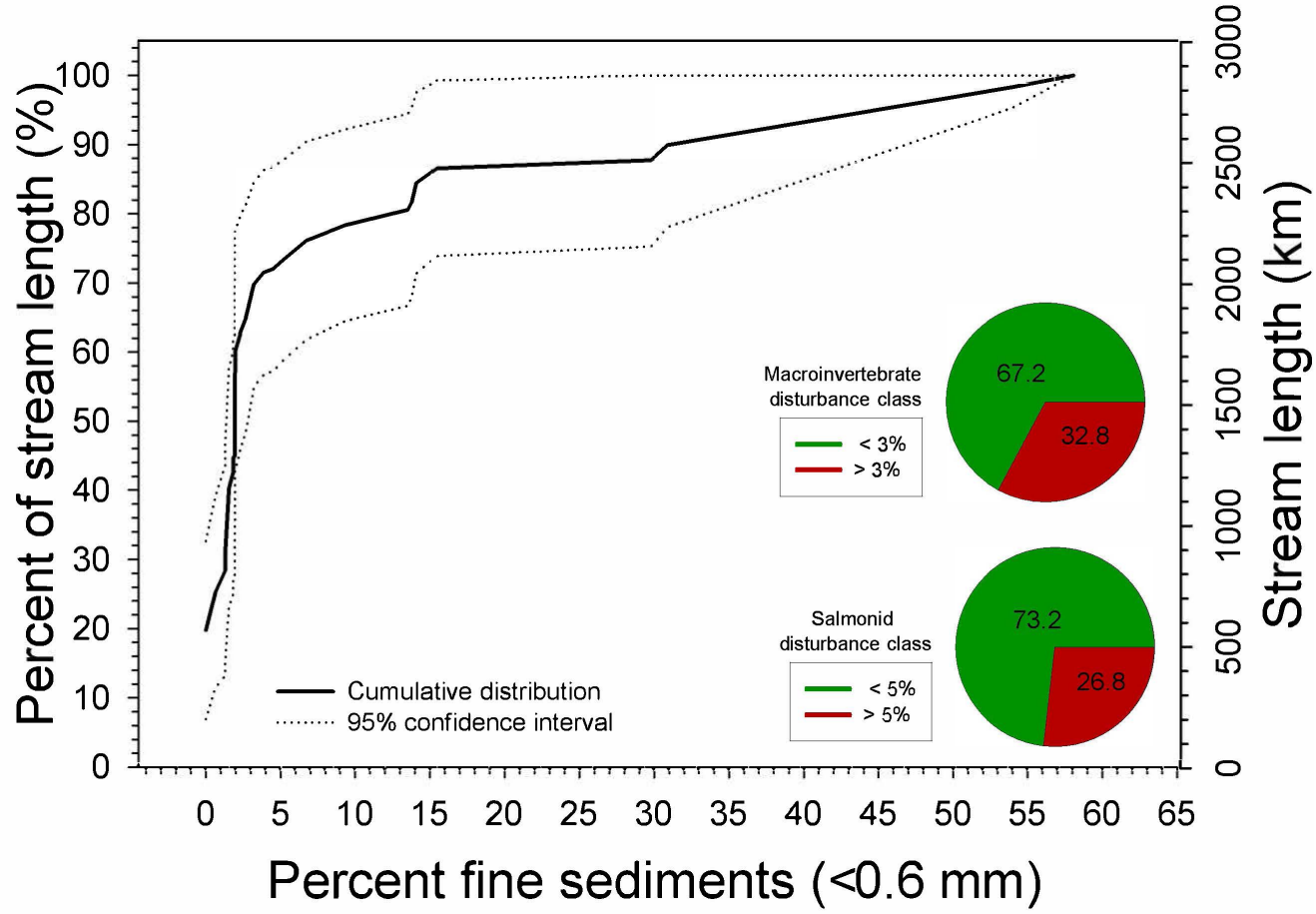


Figure 37. Cumulative distribution of percent fine sediments (also called silt and finer; <0.6 mm in diameter) in the population of Glacier National Park streams, 2007–2009. The left y-axis gives the percent of streams in the park and the right y-axis shows the actual estimated length of stream. A 95% confidence interval (dotted lines) around the percent values (heavy line) is also shown. Pie charts show the percentage of the total length in macroinvertebrate (top) and salmonid (bottom) disturbance classes from ecological thresholds in Bryce et al. (2010) as dark green (minor disturbance) and red (major disturbance). Pie charts do not include a confidence interval for each estimate in these classes, so they should be used with caution.

suggest that excessive fine sediment loading is present (or the site is "fining"; a site with too many coarse sediments is "armoring"). RBS is a key component of habitat structure for aquatic organisms. Species are adapted to natural streambed movement – too much or too little can cause stress and led to reduced ecological integrity. Because RBS depends on both the supply of sediment and the capacity for sediment to be transported, it may have a direct connection to many anthropogenic disturbances and is a useful synthetic measure of sediment dynamics. We develop a model RBS below that connects this important response in the park's streams to natural and human drivers.

Following Kaufmann et al. (1999) and Kaufmann et al. (2008), we estimate RBS as the log ratio of observed geometric mean bed surface particle diameter (from 155 substrate particles classified by field crews) and the "critical" or mobile particle diameter estimated for a stream flow that is likely to mobilize the streambed. To estimate the critical bed particle diameter in a natural stream, we first estimate shear stress (an average streambed tractive force) using SEI data on bankfull flow depth, slope, channel shape, and channel roughness (including the mitigating role of large woody debris and channel complexity; Simons and Senturk 1977; Kaufmann et al. 2008). By using the modeled critical particle diameter, RBS is in effect based on the expected conditions at each site in Glacier.

Values of RBS for a given stream type and geoclimatic setting can be either too low (finer, more unstable streambeds) or too high (coarser, more stable streambeds) than expected with minor disturbance. We define assessment points on both sides of the RBS gradient from ecoregional sites (Figure 38 shows this graphically). Because we set ecoregional as-

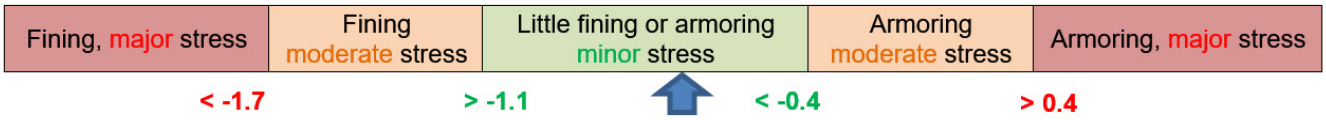


Figure 38. Arrangement of major and minor assessment points for relative bed stability. Fining happens when excessive fine sediment loading is present and armoring is the presence of too many coarse sediments. Unlabeled orange regions are intermediate between reference and non-reference states. Blue arrow indicates approximate location of median Glacier relative bed stability value in 2007–2009.

sessment points on both sides of the gradient in RBS, we feel that we meet our assumption of a linear relationship between the response and disturbance by evaluating this more complex relationship on both sides of its distribution. Lower than expected streambed stability may result either from high inputs of fine sediments (i.e., when the anthropogenic supply of sediments from the landscape exceeds the ability of the stream to move them downstream) or increases in flood magnitude or frequency. Low RBS resulting from hydrologic alteration can be a precursor to channel incision. In contrast, high bed stability is typified by hard, armored streambeds, such as those often found below dams where fine sediment flows are interrupted or within channels where banks are highly altered (e.g., paved or lined with rip-rap).

About 55% of the stream in Glacier was in a minor disturbance class (the sum of the proportion of stream length with measured sediment close to an expected size class, i.e., not fining or armoring, Figure 38 and Figure 39). In contrast, about 19% of park streams tend towards fining or armoring (with the balance in an intermediate class). However, interpretation of these values must be done with caution and, as with all ecoregional assessment points, likely best used as baselines for future comparison. For example, fining channels can occur at streams with a source of anthropogenic sediment, such as our site on McDonald Creek (see Figure 25) where the stream is next to the Going to the Sun Road and road maintenance may lead to sediment input into the channel. However, fining may also occur on wilderness streams with no known human disturbances, such as our site on the upper Saint Mary River (Figure 40). We know of few, if any, anthropogenic stressors in the park that would lead to channel armoring.

Signal : noise

With the exception of percent fines, the S:N ratios for our substrate metrics were adequate and comparable to EMAP, suggesting that these metrics estimate substrate conditions in Glacier with acceptable precision. Fines are moved more readily in most channels and thus likely vary with stream flow, potentially complicating this metric's utility (this is in part why we also use a sand and finer substrate size class).

3.7.3.5 Floodplain interaction

Largely based on approaches taken by other monitoring programs that have developed methods for evaluating stream channels and floodplains in Rocky Mountain region streams (Stoddard et al. 2005; Madej 2001 and Kaufmann et al. 1999), we use four metrics of the interactions between stream channels and their floodplains. These include (1) channel sinuosity, 2) incision, 3) bankfull width to depth ratio, and 4) bankfull width to wetted width ratio.

Channel sinuosity

Channel sinuosity of a stream or river reach is the ratio of channel length as the water flows divided by the straight-line distance between the two ends of a defined reach. The greater the sinuosity the slower water flows through a valley and the more chance it has to interact with the terrestrial landscape. Channel straightening decreases sinuosity, increases channel slope, and can lead to lower relative bed stability (fining), greater sediment transport, increased bank instability, channel downcutting, and downstream flooding.

We assessed sinuosity and floodplain interaction using ecoregional assessment points. Around 17% of the park's streams had sinuosity below a major disturbance assessment point of 0.005, while around 58% had volumes above a minor stress level of 0.03 (Table 16). The balance of about 5% was in a moderate disturbance class, with sinuosity between these two assessment points. The median log sinuosity in Glacier was 0.04, with a maximum around 0.53 recorded in a Belly River site (Figure 41a). One of the lowest values was at our site on a tributary to Railroad Creek (Figure 41b) – with a channel clearly constrained by the road grade. However, other sites with lower sinuosity are due more to natural confinement. We suspect that, in general, streams in Glacier have not been subjected to extensive human disturbances that have reduced sinuosity.

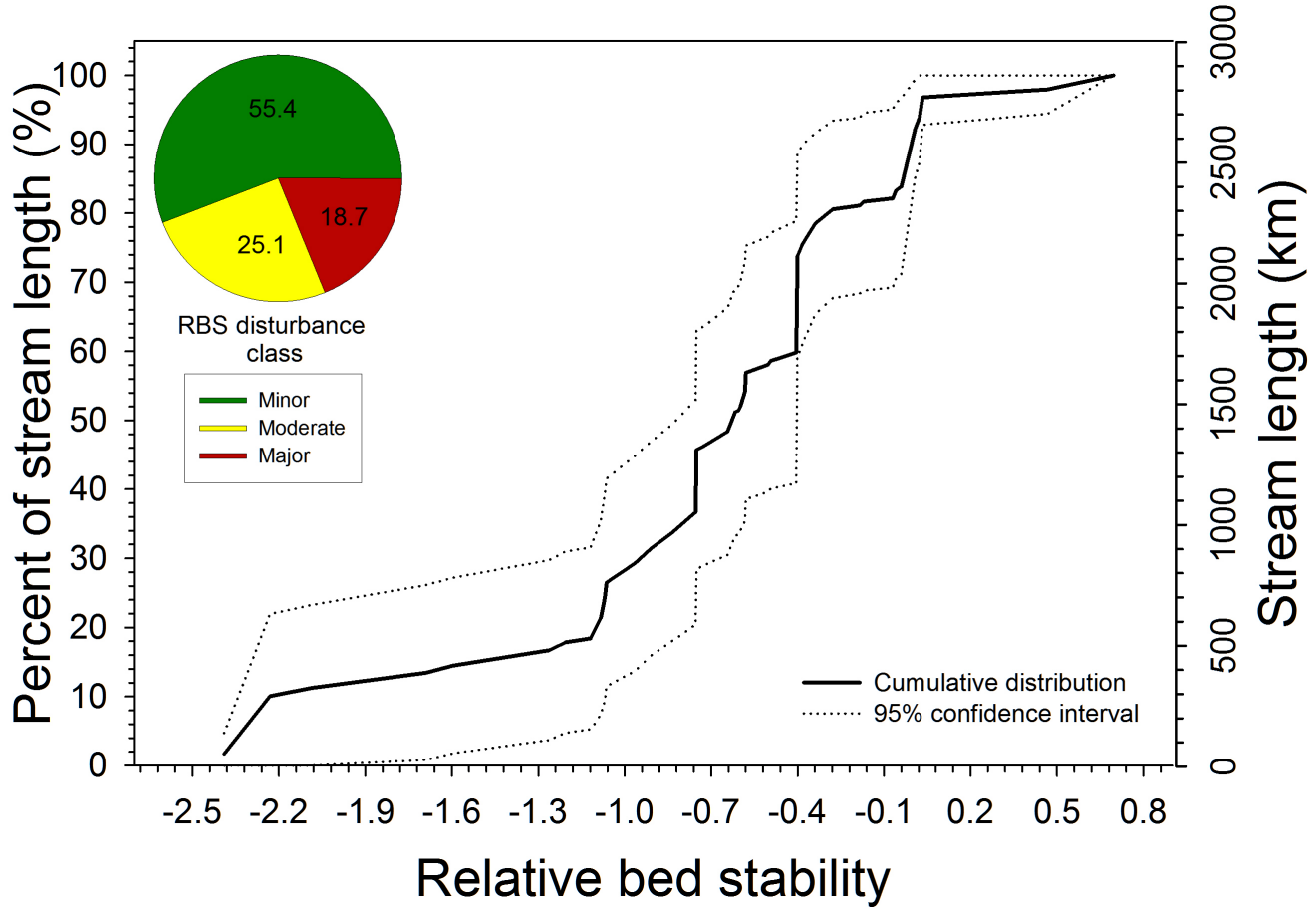


Figure 39. Cumulative distribution of relative bed stability (RBS) in the population of Glacier National Park streams, 2007–2009. The left y-axis gives the percent of streams in the park and the right y-axis shows the actual estimated length of stream. A 95% confidence interval (dotted black lines) around the percent values (heavy line) is also shown. Pie chart shows the percentage of the total length in major (red), moderate (yellow), and minor (dark green) disturbance class, with values in each class summed across each end of the RBS gradient. Pie charts do not include a confidence interval for each estimate in these classes, so they should be used with caution.

Incision

Stream incision results when bankfull stage is at a lower elevation than the top of the stream bank and is usually caused by an increase of the erosive ability of a river, a decrease in the bedload sediment supply, or when the stream bottom and banks are destabilized by disturbances – either natural or human caused (Poff et al. 1997; Simon and Rinaldi 2006). Note that given methodological issues in 2007 and 2008, the sample size for our incision estimates was only six and these results should be used with caution. However, based on our experience with sites sampled in 2007 and 2008 we feel that our limited results from 2009 are representative.

Our results suggest that incision in the streams in the park was below (recall lower incision is assumed to indicate reduced disturbance) a minor disturbance level of 0.80 m (Table 16). The median incision in Glacier was 0.47 m, with a



Figure 40. Example of a site with fining relative bed stability (not visible) but with no known human disturbance, St Mary River, 2008, Glacier National Park. (NPS/I. ASHTON).



Figure 41. Examples of stream sites in Glacier National Park with a) high degree of sinuosity (Belly River, site G04) and b) low sinuosity, with a clear human disturbance cause (tributary to Railroad Creek, site G032). In both images the sample reach over which sinuosity was calculated extends from the top of the image to the bottom. The difference in reach scale or extent is accounted for in the sinuosity metric. Images are from late summer 2005 (USDA 2005).

maximum around 0.74 m at a site on Apgar Creek near Lake McDonald. The Apgar site is interesting as it is both near the Camas Road and was likely strongly affected by the Robert Fire of 2003. While the fire's effects on water chemistry were more short term (Clow and Mast 2008), impacts to sediment dynamics that can influence incision can often be longer term from a fire as severe as this one (Figure 42). However, this site is likely an exception, as in general, most channels had few to any indications of problematic incision. We do not think streams in Glacier have been subjected to extensive human disturbances that have increased incision.



Figure 42. Effects of the Robert Fire, 2003, Glacier National Park. Image shows high burn intensity that disturbed many soils and likely contributed excess fine sediment to local streams, like Apgar Creek, that can lead to channel incision. (NPS/Glacier National Park).

Bankfull width to depth ratio and bankfull width to wetted width ratio

Our last two metrics of the interaction between stream channels and their floodplains, bankfull width to depth ratio and the bankfull width to wetted width ratio, are integrators of channel response to changes in sediment supply and transport, with important relationships to over bank flooding, channel shading, hyporheic flow (Kasahara and Wondzell 2003), stream temperature (White et al. 1987), and deepwater habitat refugia for fish (Montana DEQ 2011). Bankfull width to wetted width estimates the potential for inundation from floods – sites with wide lateral bars reduce the likelihood of smaller floods reaching into the floodplain. In most stream types in more intact systems like Glacier, channels are characterized by lower width to depth ratios (i.e., channels are not a "mile wide and an inch deep" like they can naturally be in lower elevation areas), with less extensive lateral bars separating wetted and bankfull width (Rosgen 1984).

The median log bankfull width to depth ratio in Glacier was about 0.9 and 0.1 for log bankfull width to wetted width and bankfull width to wetted width (Table 16). Around 9% and 2% of the park's streams had bankfull width to depth ratio and bankfull width to wetted width (respectively) in a major disturbance class. Around 84% and 76% were in a minor stress class (Table 16). We do not think either of these values indicate meaningful issues with human caused imbalances in sediment and discharge dynamics that would increase width to depth ratios or extend bankfull widths beyond measured wetted widths. The higher percentage (9%) of streams with wider channels may be due to several rivers in our sample that are naturally larger when compared to ecoregion reference sites that tend to be smaller higher gradient streams.

Signal : noise

S:N was unacceptable for incision, but this is likely due mostly to our small sample size for this specific metric. It was also low for sinuosity, which likely reflects the inability to use engineering grade methods in the remote setting of most SEI sites. Values for the floodplain interaction metrics were acceptable, suggesting that they are estimating these aspects of the streams in Glacier with good precision.

3.7.3.6 Stream flow and habitat based indicators of hydrologic regime

Hydrologic regime, or the amount and timing of stream flow, and its interaction with other elements of stream habitat, are fundamental components and determinants of the condition of streams. Human use of water (i.e., withdrawal for irrigation) can cause stress to stream ecosystems (Poff et al. 1997) when changes in hydrology disrupt reproduction, survival, spawning, and migration of biota (Poff and Ward 1989; Junk et al. 1989).

We measure instantaneous stream flow with every full sample event and harvest continuous discharge data from any nearby USGS or other stream gauge where available. We present trend models of continuous discharge at select sites in Schweiger et al. (in preparation a). Following Stoddard et al. (2005), we use two general metrics derived from habitat data as indirect indicators of hydrologic regime. These include 1) the ratio of base summer flow to annual mean runoff as an index of "droughtiness," and 2) the ratio of bankfull depth to wetted depth as a morphometric index of "flashiness." The droughtiness index describes how much smaller base flow (when SEI samples are collected) is than annual mean flow. The flashiness index compares the range of variation between low and high flows using bankfull flow compared to wetted depth. Both metrics are approximations to true

estimates of a site's hydrologic regime (i.e., Baker et al. 2004), such as what is available where there is a long-term record of stream flow, yet they offer an integrated habitat response perspective to classic measures of hydrology.

Droughtiness

Instantaneous base flow discharge in park streams spanned a wide range, from very low in sites like Rubideau Creek tributary, to large volumes of water on our mainstem sites of the North and Middle Forks of Flathead River. This is expected given the breadth of stream types and watersheds we sampled in the park. There are no relevant assessment points for instantaneous discharge; however, in general we did not see any issues with base flow discharge in the park's streams during this time period. Of note, 2007 was a dry year and 2008/2009 fairly wet, so these may have "balanced each other out" over the survey period. More informative analyses are possible with long-term time series data of stream flow as presented in Schweiger et al. (in preparation a) and Mills et al. (2011). In summary, this research suggests that most gauged streams in the park show a seasonally adjusted decreasing trend in discharge, but that most models are not statistically significant.

The median log ratio of low flow to annual mean runoff (inverse index of "droughtiness") was -2.1 (a raw value of 0.01) for the population of Glacier streams in 2007–2009 (Table 16). This suggests that the typical base flow in the park is around 1% of its mean annual runoff. While this seems low, about 69% of the Glacier stream resource is below this, or in a minor disturbance (droughtiness) class, suggesting that drought risk is lower in most of the park's streams than in surrounding ecoregion reference sites. Only 14% of the park's streams were in a major disturbance class (with higher droughtiness) relative to ecoregion reference sites. This is expected for most streams in Glacier given the park's high elevation and high levels of precipitation, especially on the park's mesic west side, and minimal human modification (i.e. water diversion) that might increase drought risk.

Flashiness

The median log ratio of bankfull height to wetted depth ("flashiness") was 0.44 for the population of Glacier streams in 2007–2009 (Table 16). This suggests that the typical channel in the park is about three times deeper than its bankfull height (bankfull height is measured from the water surface). More flashy channels often have higher bankfull heights given the erosive power of extreme flows. Thus, while extreme events can certainly happen in the park's streams, about 60% of the stream in the park was below (less flashy) the minor disturbance level (a log value of 0.6 or bankfull about 4x mean depth) seen in ecoregional reference sites, and only about 1% was in a major disturbance class (with a log ratio of 2 or around 100x in a non-log scale). The streams in the park with this high of a of bankfull height to wetted depth ratio are the mainstem of the North and Middle Forks of Flathead River. However, these sites do not have any meaningful human disturbance that might cause this flashiness. Rather this likely reflects their large watersheds that store large volumes of water that can be released in high flows (Figure 43).



Figure 43. Middle Fork of the Flathead River at the Belton Bridge, Glacier National Park, 2011. Image shows river near flood stage. (GLACIER NATIONAL PARK/DAVID RESTIVO).

Signal : noise

The S:N of instantaneous base flow discharge was surprisingly high given daily variation in discharge. This is an important result and suggests that spreading our sample across three summer index periods may have had less of an effect on our results. S:N for the droughtiness index was low, but very good for the flashiness index, suggesting that these estimate conditions in Glacier with mixed precision.

3.7.3.7 Riparian vegetation cover

The importance of riparian vegetation to channel structure, cover, shading, nutrient inputs, large woody debris, wildlife corridors, and as a buffer against anthropogenic disturbance is well recognized (Naiman et al. 1988; Gregory et al. 1991). Riparian vegetation moderates stream temperatures through shading, increases bank stability, and provides coarse and fine particulate organic material. Organic inputs from riparian vegetation become food for stream organisms and provide structure that creates and maintains complex channel habitat. Understanding and monitoring invasive/exotic

taxa in riparian systems is key for park resource management as the connectivity afforded by the stream network provides an additional pathway for invasion of riparian vegetation to a broader landscape (Merritt and Wohl 2002; Ringold et al. 2008). Invasive/exotic riparian taxa have been associated with multiple negative effects (Ringold et al. 2008), including: 1) alteration of fire, nutrient, or hydrologic regimes; 2) excess carbon sequestration; 3) changes to plant and animal distributions; or 4) repelling or sickening livestock.

Following Stoddard et al. (2005) and Ringold et al. (2008), we used four metrics describing riparian vegetation in Glacier. These metrics are: 1) total vegetative cover on the bank/shoreline, 2) total areal cover of the riparian vegetation in canopy, mid-level, and ground layers, 3) total areal cover of riparian woody vegetation in canopy, mid-level, and ground layers, and 4) the presence of invasive/exotic plants. Note that this last metric is also an indirect measure of human disturbance in riparian corridors. We use total cover on the bank (versus mid-channel as in Stoddard et al. (2005)), as this is more appropriate for the larger rivers naturally too big for a mid-channel canopy, and because it integrates all natural cover (not just vegetation) at about 30 cm from the ground (Figure 44). It is a better metric of cover that can be important in alpine and other naturally sparsely vegetated areas in the park (Vannote et al. 1980). The other two metrics estimate total and more long lived woody components in the canopy and shrub layers within the riparian zone proper.



Figure 44. Rocky Mountain Network Stream Ecological Integrity field crew collect data on stream canopy cover using a densiometer. (NPS/BILLY SCHWEIGER)

Stream bank vegetation cover

The median stream bank vegetation cover was about 59% for the population of Glacier streams in 2007–2009 (Table 16). Bankside cover ranged from close to 0 (Divide Creek, Figure 45 and Figure 46) to almost 90% at several sites, including a tributary to Lincoln Creek, Apgar Creek, and a tributary to Rubideau Creek. We used ecoregional reference sites to assess these metrics. Around 85% of the bankside cover in Glacier was above a minor disturbance level of 17%, with only about 10% below the major disturbance cover level of 5.6%. This suggests that most of the stream in the park had more extensive bankside cover of natural features than reference sites in the park's ecoregions. We feel that most of the bankside cover in the park is not impacted by human disturbance. However, there are select sites (Divide Creek being a good example) where visitor services or other human driven disturbances has impacted cover. Interestingly, some of the other sites in the park that show more stressed responses for other metrics (i.e., our site on a tributary to Rubideau Creek near the West Glacier water supply with potential nutrient issues, see 3.6.3.4) have high bankside cover, suggesting it may buffer human disturbances to the stream.

Total vegetation cover

The median total vegetation (defined as canopy plus the middle layer plus a ground layer) cover was over 100% for the population of Glacier streams in 2007–2009 (Table 16). The range was from 41% (at Divide Creek) to 230% (values over a total of 100% are possible as each layer is summed to a theoretical maximum of 300%). The highest cover value was at a site on the South Fork of Cutbank Creek (Figure 47). Around 60% of the total riparian cover in Glacier was above a minor disturbance level of 90%, with about 5% below a major disturbance cover level of 50%. The relatively low percentage of streams in a minor stress category likely reflects our inclusion of stream types with naturally low cover, such as in the alpine. However, there are a few select front country streams in the park that may have had riparian vegetation removed or may have been impacted from human disturbance (i.e., Divide Creek, see Figure 45).

Woody vegetation cover

When riparian vegetation is restricted to woody species, the median proportional cover value was about 0.7 for the population of Glacier streams in 2007–2009 (Table 16). Patterns in this metric were similar to total vegetation. Around 70% of the woody riparian cover in Glacier was above a minor disturbance level of 0.6, with about 9% below a major disturbance cover level of 0.2.Woody cover is an important potential source of nutrients and structure in streams, and this is a habitat attribute that will need to be carefully tracked over time.

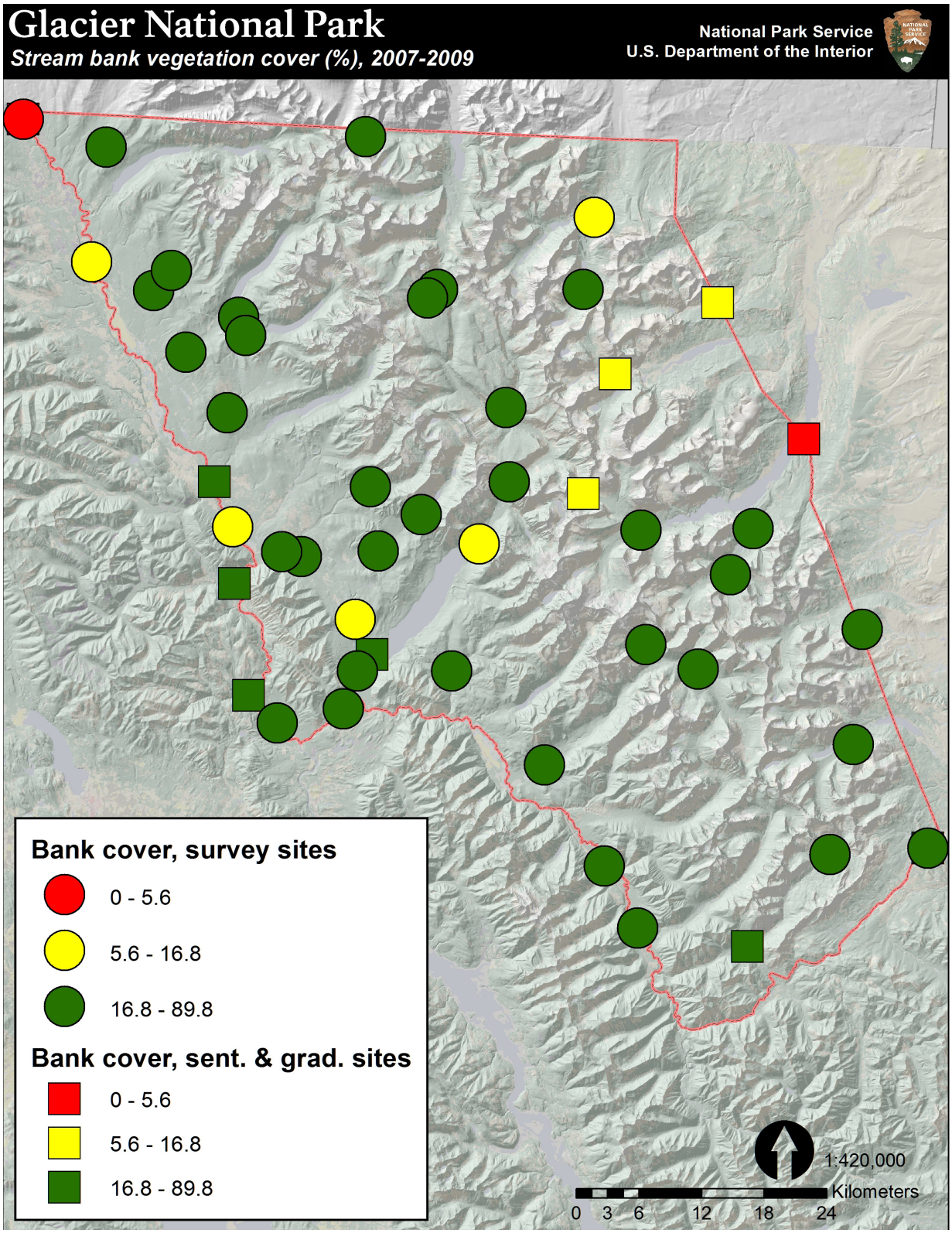


Figure 45. Map of bank vegetation cover (%) at Stream Ecological Integrity survey, sentinel (sent.) and gradient (grad.) sites in Glacier National Park, 2007–2009. The three colored condition classes are based on assessment points defined from ecoregional stream sites in an expected or a priori reference state in the park and its surrounding ecoregions. Red indicates sites with the least percent cover. See Appendix A for a complete list of site numbers and names.

Invasive/exotic riparian plants

Finally, we use the presence of invasive/exotic plants as both indicators of human disturbance and measures of an important component of riparian vegetation. This is an important and high visibility indicator for stream monitoring in the park. Riparian systems are of special interest for monitoring status and trend in invasive/exotic plants for three reasons (Ringold et al. 2008). First, riparian areas may be more likely to be invaded than upland ecosystems (Brown and Peet 2003), given higher levels of both natural and anthropogenic disturbance (Hobbs and Huenneke 1992; Mack 2000; Nilsson and Svedmark 2002). Second, connectivity created by a stream network facilitates dispersal across a landscape (Merritt and Wohl 2002; Nilsson and Svedmark 2002). Third many invasive/exotic species can alter stream ecosystems (i.e., Zavaleta 2000). Note that we also report on select aquatic invasive/exotic species in the bioassessment section (3.8.4) below.

Invasive/exotic species lists were developed with Glacier staff. The list includes 15 taxa (including a three species complex for Meadow hawkweed (*Hieracium pratense, H. floribundum, H. piloselloides*) that are ecologically varied, easy to identify, truly invasive/exotic, and ecologically or economically intrusive. In addition, some of the taxa are included in regional surveys like EMAP (Ringold et al. 2008), which, although there are important methodological considerations in using these data from ecoregional reference sites, expands our ability to understand patterns in invasive/exotic plants in Glacier.



Figure 46. A patch of invasive/exotic spotted knapweed (*Centaurea maculosa*) on Divide Creek on the east side of Glacier National Park, 2007. (NPS/BILLY SCHWEIGER)



Figure 47. South Fork of Cutbank Creek, Glacier National Park, 2008. Image shows naturally high riparian cover of all vegetation types. (NPS/DONNA SHORROCK)

Nine of the target taxa in Glacier are Category 1 on the state noxious weed list (Montana Fish, Wildlife and Parks 2008; USDA 2017). Category 1 taxa are generally widespread in the state and are well adapted to a wide range of site conditions. They are noxious, rendering land unfit or greatly limit beneficial uses. The Montana Weed Management Plan lists widespread infestations of such Category 1 weeds as a third (or lower) priority for management, given their widespread nature and difficulty of control. Management criteria include public awareness and education, containment, and suppression of existing infestations and prevention of new infestations. The other six taxa are Category 2 species that have recently been introduced into Montana and/or are rapidly spreading from current infestations. They are also considered noxious, rendering land unfit or greatly limiting beneficial uses. Management criteria include awareness and education, prevention of movement into non-infested areas, monitoring and containment of known infestations, and eradication where possible. Their control is of a higher priority, given a greater possibility of success.

Table 17 gives the mean frequency of each of the 15 taxa targeted at Glacier. Counts are taken across up to 22 possible riparian plots at a site – a frequency of 1 within a site means that the species was recorded as present in all plots. We use all events from all site types from 2007 to 2009 to increase the likelihood of detection. Nine taxa were observed at least once across all events. Spotted knapweed and Canada thistle were the most commonly recorded taxa, occurring with an average frequency of 0.08 and 0.06. While SEI field data on invasive/exotics do not quantify abundance, anecdotally, a few events documented taxa in fairly large patches. In particular, Spotted knapweed (Figure 46), Canada thistle, Oxeye daisy (*Chrysanthemum leucanthemum*) and St. Johnswort (*Hypericum perforatum*) (Figure 48) were occasionally relatively widely distributed within a sample reach. The metrics in Table 17 are not inferred across all streams in the park, given the low occurrences of individual species. They are also perhaps more useful at the site scale where park management of invasive/exotic taxa occurs. Additional information, such as the list of taxa at a site, is available upon request from the network.

We develop a composite metric (Invasive Plant Index; IPI) of the summed frequency of all target invasive/exotic taxa along each Glacier sample reach as a more comprehensive assay of

Table 17. Mean frequency (% of transects occupied) of 15 target invasive/exotic plant taxa at Glacier National Park during 2007–2009, along with standard error (SE). Values are taken across all 87sample events from 2007–2009 during physical habitat data collection to increase detection probability. Montana Weed Category is from Montana Fish, Wildlife and Parks (2008). Category 1 is widespread noxious weeds and Category 2 is established new invaders.

Taxa	Montana Weed Category	Mean %	SE	Minimum	Maximum
Spotted knapweed (*Centaurea maculosa*)	1	0.084	0.0232	0	1.000
Canada thistle (*Cirsium arvense*)	1	0.063	0.0156	0	0.889
Oxeye daisy (*Chrysanthemum leucanthemum*)	1	0.049	0.0160	0	0.909
St. Johnswort (*Hypericum perforatum*)	1	0.034	0.0140	0	1.000
Meadow hawkweed complex (*Hieracium pratense*, *H. floribundum*, *H. piloselloides*)	2	0.033	0.0102	0	0.545
Common tansy (*Tanacetum vulgare*)	1	0.009	0.0069	0	0.636
Yellow toadflax (*Linaria vulgaris*)	1	0.008	0.0047	0	0.385
Orange hawkweed (*H. aurantiacum*)	2	0.004	0.0022	0	0.167
Dalmatian toadflax (*Linaria dalmatica*)	1	0.002	0.0014	0	0.091
Leafy spurge (*Euphorbia esula*)	1	0	0	0	0
Houndstongue (*Cynoglossum officinale*)	1	0	0	0	0
Purple loosestrife (*Lythrum salicaria*, *L. virgatum*)	2	0	0	0	0
Tall buttercup (*Ranunculus acris*)	2	0	0	0	0
Tansy ragwort (*Senecio jacobea*)	2	0	0	0	0
Japanese knotweed (*Polygonium cuspidatum*)	2	0	0	0	0

invasion and estimate its value for the population of streams in the park. IPI values at a site range from a theoretical maximum of 15 if all taxa occurred in all 22 riparian plots at a sample site, to 0 if no taxa were found in any plot. The array of combinations behind a given index value is complex and it should be interpreted with caution. For example, if one species was found at all plots the value is 1.0. If two taxa were found, each at half the plots, the value would also be 1.0. If one species was found at 11 (out of 22) plots, the value is 0.5. However, we feel it is a useful index to assess overall invasion status.

Even given the well-defined regulatory context for invasive/exotic plants, there are no regulatory criteria or known ecological thresholds for individual taxa or the specific IPI metric. Comparisons to ecoregional assessment points are also complicated if lists of target taxa differ, as they do, across SEI, EMAP, and NRSA (EPA National Rivers and Streams Assessment). However, we develop a meaningful ecological threshold based assessment point for IPI along the lines of our approach to the human disturbance index by assuming that a negligible stress assessment point occurs where there are no (zero) occurrences of any invasive/exotic taxa. This assumes that the reference state is for none of these species to be present at all. This is in keeping with the NPS approach to managing invasive/exotic plants (NPS 2006b; see also Ringold et al. 2008). Above this threshold (i.e., where at least one taxon occurs once in a site) we have no real way of setting assessment points and focus on comparisons in IPI across time (and only if the target species list remains the same).

The median value for the IPI for the population of streams in Glacier in 2007–2009 was 0 (meaning that approximately half of the values were 0 in the distribution). Given the importance of non-zero and outlier values (e.g., sites with heavy invasions that a median statistic may not reflect) in this metric, we also report a population scale mean of 0.23. The minimum site scale value was zero, which was typical at backcountry wilderness sites (Figure 49). The maximum value was 1.7 for survey sites (Railroad Creek tributary) and 2.0 for sentinel or gradient sites (Divide Creek, Figure 46 and Figure 49). Around 62% of the park's streams were weed free or in a negligible stress class (Figure 50).

We can make one species level comparison to patterns across the Northern and Canadian Rockies ecoregions for Canada thistle, as this taxon was also included at both SEI and EMAP sites. Canada thistle had an average frequency of 0.06 within sites where it occurred compared to 0.03 at EMAP



Figure 48. The invasive/exotic plant, St. Johnswort (*Hypericum perforatum*), on the banks of McDonald Creek in Glacier National Park, 2008. The site is near Going to the Sun Road. (NPS/BILLY SCHWEIGER)

sites. Therefore the degree of thistle invasion across all sites in Glacier where it occurred was higher than at reference sites in the park's ecoregion. This suggests that for at least this species, the extent and degree of invasion in the park is greater than across the ecoregion. Canada thistle, while a Category 1 species, is naturalized in the park. This species prefers mesic riparian areas, which characterize much of Glacier. This may explain its greater degree of invasion in the park relative to ecoregion sites.

Caveats

There are some important caveats for our results here. SEI data on invasive/exotic riparian plants are relatively simple and should not replace efforts by Glacier to monitor and manage this issue. Most importantly, SEI sites were not targeted towards areas with higher probability of invasion and we likely miss many of these local scale invasions. Finally, we do not conduct complete surveys of the vegetation in and around our sites because this would be cost and time prohibitive.

Signal : noise and other estimates of precision

The S:N of IPI was marginal, at 1.2, suggesting the index has reduced precision. Weeds are often irruptive or may be easily missed by stream crews more focused on more classic aquatic elements of the protocols. Ringold et al. (2008) reports on several additional analyses looking at the precision of the invasive/exotic plant element of the EMAP protocol (very similar to SEI). For example, they include a comparison between expert botanist crews surveying the complete vegetation at six EMAP sites in Montana also evaluated by

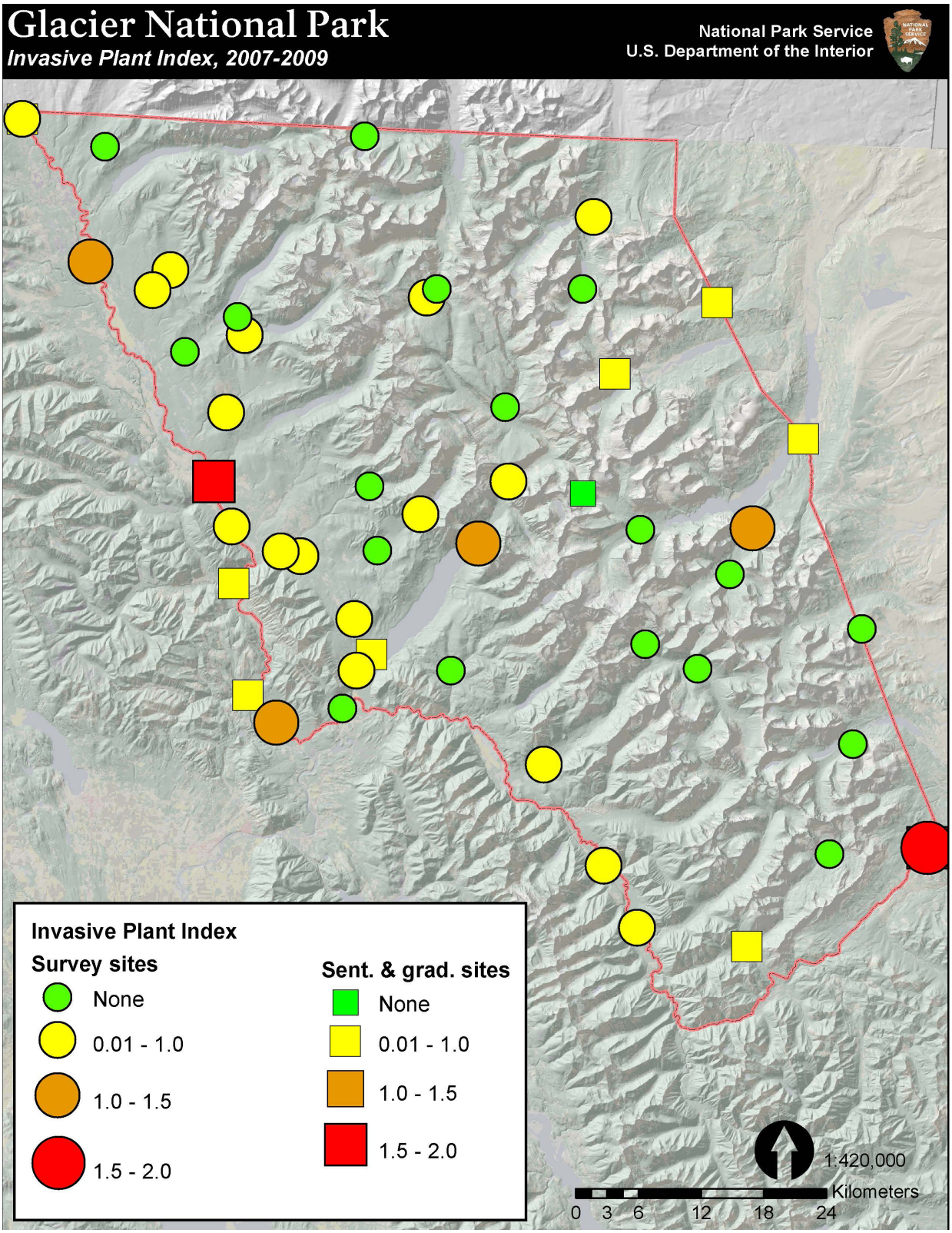


Figure 49. Invasive Plant Index (IPI) at Stream Ecological Integrity sites in Glacier National Park, 2007–2009. We use assessment points set at a negligible ecological threshold of 0 (no invasive/exotic taxa). We further divide the symbology at sites with at least one occurrence of an invasive/exotic plant using a natural breaks classification (Jenks 1967). Higher index scores (more invasion) are represented by larger symbol size and brown to red colors. See Appendix A for a complete list of site numbers and names.

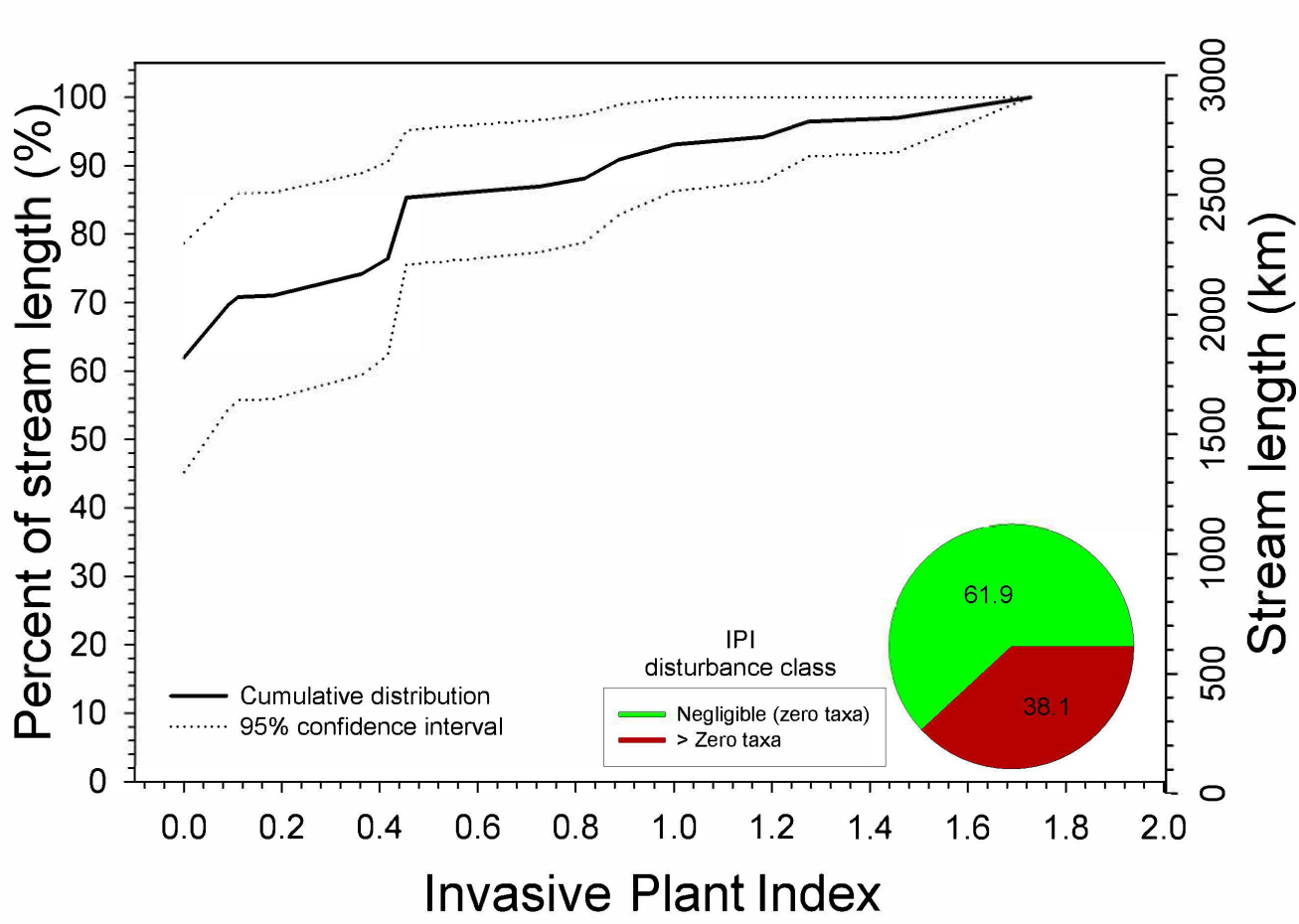


Figure 50. Cumulative distribution of the Invasive Plant Index (IPI) in the population of Glacier National Park streams, 2007–2009. The left y-axis gives the percent of streams in the park and the right y-axis shows the actual estimated length of stream. A 95% confidence interval (dotted lines) around the percent values (heavy line) is also shown. Pie chart shows the percentage of the total length in a negligible disturbance class (light green) and in a major disturbance class (red). Pie charts do not include a confidence interval for each estimate in these classes, so they should be used with caution.

stream crews. They conclude that around 92% of the occurrences seen by botanical crews were also seen by stream crews, suggesting that the EMAP (or SEI) protocol provides comparable data to extensive botanical work. We hope that our SEI crews are as good (or better) than EMAP crews, but we do not have these same data at Glacier SEI sites. However, beginning in 2009, our stream crews often included the park's main field botanists and at least anecdotally they indicate that our stream technicians did a good job locating and identifying target invasive/exotic taxa. Finally, we calculated a mean relative precision across all revisits to the same sites – perhaps a better statistic than S:N of the IPI for individual species presence/absence records. This is simply the mean of all identical presence (or absence) records of each of the 15 taxa across all revisits in our dataset. SEI crews on average found (or did not find) 94% of the same taxa across all revisits. This suggests our crews did an acceptable job estimating invasive/exotic plants at Glacier stream sites.

3.7.4 Exploratory models of physical habitat

Next, we present example models of stream physical habitat indicators. We focus on pool depth as an indicator of habitat volume (see section 3.7.3.1 above) and relative bed stability as an indicator of sediment, given the importance of these attributes to the ecology of Glacier's streams and their possible management utility. Additional models of other habitat metrics are available from the network upon request. We selected potential independent variables in each model based on our collective ecological experience, statistical attributes, and those that we believe have the most utility for stream resource management in Glacier. For additional details on model construction, see the methods, Appendix

F, and/or the introduction to this subject within the human disturbance section above (3.5.4). We use conditional plots of partial residuals to visualize the models (Larsen and McCleary 1972; Breheny and Burchett 2013).

3.7.4.1 Observed : expected pool depth (habitat volume)

Pool depth is controlled to a large degree by the size and power of a stream, which in turn naturally vary with drainage area, runoff, and slope (Stack and Beschta 1989). We estimated an expected mean pool depth at all Glacier sites using a model developed by the EPA within the EMAP program (Stoddard et al. 2005). The EMAP model was derived from data collected at over 1000 stream monitoring sites across the West (including the sites used in this report for ecoregion assessment point derivation). It predicts mean pool depth from basin area, long-term mean annual precipitation, channel slope, and lithology. We then calculated the ratio of observed values in pool depth to their expected score estimated from the EMAP model. The variables within the EMAP model of expected pool depths are all arguably natural in Glacier streams (patterns in precipitation over the long term have an anthropogenic component via climate change), and we would expect this ratio to be around 1.0 should there not be any human disturbances impacting habitat volume in streams. We therefore treat the ratio as an ecologically meaningful measure of habitat condition at a site, interpreting deviations from 1.0 as possible indications of human stress on streams in Glacier. To better understand the potential drivers behind this relationship, and to statistically remove any confounded natural drivers from human disturbance's potential effect, we model the ratio as a function of select environmental and human disturbance variables that may predict or covary with patterns in the ratio.

Values of the ratio of observed pool depth to their expected depth can theoretically vary from ~1, where the observed pool depth is about what the predictive model expects (which we equate with a minor disturbance class), to zero, where there is a very small amount of pool relative to expectations (major disturbance class). A more nuanced interpretation of the gradient of ratio values between 1 and 0 (i.e., assignment of additional assessment points) will require more research. Values meaningfully above 1 indicate that there is greater mean depth at a site than expected. They may suggest negligible or zero stress, with potentially pristine reference ecological condition; however, this relationship may not be linear, as at some point there is likely "too much" pool depth (and the stream becomes more like a flat bottomed lake). This will also require more research to resolve.

The mean ratio of observed to expected pool depths was 0.89, with a minimum of 0 (Rubideau Creek tributary) and a maximum of 1.6 (Belly River). Note that these are site scale results, not inferred to the population of streams in the park. The final model of the ratio of observed to expected pool depths included seven independent variables (Table 18). It was highly significant ($p < 1.145e-05$), with an adjusted r^2 of 0.52, indicating a meaningful proportion of the variation in the ratio of observed to expected pool depths was accounted for. Complete models details are presented in Appendix F. We focus our interpretation here on select independent variables that either had high relative importance, low p-values, and/or interesting relationships as drivers or covariates of pool depth. We use conditional plots of partial residuals to visualize the model (Larsen and McCleary 1972; Breheny and Burchett 2013).

Table 18. Model of ratio of observed to expected pool depths in 2007–2009 for streams in Glacier National Park. Final model selected using Akaike Information Criterion (AIC) and expert opinion from 16 candidate variables. East vs. West is treated as a factor and all estimates are relative to the west side of the park (west); Relative importance (Rel. Imp %) is the total amount of explained variance for each variable expressed as a percentage.

Model component	Estimate	SE	t	p	Rel. Imp. (%)
Intercept	1.03	0.74	1.39	0.17	–
East vs. west (west)	-0.35	0.16	-2.18	0.04	0.09
Human Disturbance Index	-0.51	0.17	-3.05	0.00	0.18
Elevation	-8.24E-04	3.71E-04	-2.22	0.03	0.05
% glacier in catch. (log)	-0.12	0.07	-1.69	0.10	0.06
Mean water depth (log)	0.26	0.06	4.70	0.00	0.51
Coeff. of variation in water depth	0.45	0.28	1.61	0.12	0.03
Discharge (log)	0.06	0.03	2.02	0.05	0.07

Notes: SE = standard error of coefficient, t = t test value, p = probability of the t. Residual standard error: 0.26 on 36 degrees of freedom, Multiple R^2: 0.60, Adjusted R^2: 0.52, F-statistic: 7.7 on 7 and 36 DF, p-value: 1.145e-05.

Over 50% of the variation in the ratio of observed to expected pool depths was explained by the log of the mean water depth at the time of each sample, with ratios higher (observed habitat volume closer to expected based on geophysical context) with deeper mean depths (Figure 51, Table 18). This suggests (unsurprisingly) that even though we used a pool depth metric of habitat volume that is independent of water depth in its estimation (Kaufmann et al. 1999), deeper streams tend to both have greater pool depths and to better match expected pool depths.

An interesting and potentially useful result in the model was the next most important predictor: human disturbance (HDI; Figure 51, Table 18). Almost 20% of the variation in ratios was accounted for by human disturbance, with ratios lower (observed habitat volume further from expected based on geophysical context) with higher HDI. Because the model statistically accounts for other (natural) drivers, this suggests that HDI may have a meaningful impact on this important aspect of stream habitat. Most sites with low ratios were front country streams such as Rubideau and Railroad Creeks. These sites have often been examples in this report of more human disturbed sites. Sites on the western tributaries to the North Fork of the Flathead (Coal and Big Creeks) also tended to have lower ratios and higher HDI. These sites drain watersheds to the west of the park listed by Montana DEQ as not supporting aquatic life due to road construction and use and streambank modifications/destabilization as a result of forestry in the Smoky Range (Montana DEQ 2016). Importantly, these sites are on the boundary of the park and the human disturbance that impacts them is outside the park. However, their impaired condition (or their assignment to a major disturbance class using our terminology) likely matters to the condition of water bodies in the park and is suggestive of what may happen to important aspects of stream habitat with human disturbance. This said, we still must be careful with our interpretation. Two other sites (Bowman Lake and Lincoln Creek tributaries) with very low ratios (meaning less pool depth relative to expectations) also had low HDI. These sites are both somewhat unique in their geomorphic structure and naturally shallow. They had higher quality ecological integrity, supporting unique species in the park, including the Rocky Mountain tailed frog (Ascaphus montanus), which is known as an indicator of reference caliber water chemistry and unmodified stream habitat (Figure 52; Black and Timken 1976; Welsh and Ollivier 1998). It is possible the uniqueness of these streams places them outside the experience of the EMAP model estimating an expected pool depth. Such stream types may be common in the landscape of Glacier.

The model also includes the coefficient of variation in water depth and instantaneous discharge, both with a positive relationship with the ratio of observed to expected pool depths. These predictors had smaller importance values but support the interpretation that hydrology matters in how well observed habitat volumes match their expectation. Overall, while water depths can be affected by human disturbance (i.e., water drawdowns or irrigation return flows), we expect this is largely a naturally varying aspect of stream physical habitat in Glacier and thus not an area of concern, with the rare exception of sites that may have anthropogenic modification of hydrology.

Finally, the percentage of active glaciers in a site's catchment was negatively related to the ratio of observed to expected pool depths. Elevation was also in the model, thus this pattern is not statistically confounded with the elevation of streams. This may suggest that basins with a glacier influenced hydrology (more glaciers) might have streams with more natural habitat volume (more observed deep pools than expected). This may be a potentially important link to shifting climate regimes and the subsequent loss of glaciers, and thus should be an ongoing focus of work on streams in Glacier.

3.7.4.2 Relative bed stability

We next develop a model for relative bed stability (RBS), or the tendency of streambed particles to resist transport under a given stream flow. RBS is a useful synthetic metric of sediment dynamics in a stream. Much like the ratio of observed to expected pool depths presented above, our RBS metric incorporates deviation from what a site "should" have under minimal disturbance or reference conditions. For RBS, the expected state is based on the mobile particle diameter for a given stream flow that, based on geomorphic characteristics of the site, is likely to mobilize the streambed (Simons and Senturk 1977; Kaufmann et al. 2008).

The final model for relative bed stability included seven independent variables (Table 19). It was highly significant ($p < 8.277e-05$), with an adjusted r^2 of 0.79, indicating most of the variation in relative bed stability was accounted for in the model. Complete models details are presented in Appendix F. We focus our interpretation here on select independent variables that either had high relative importance, low p-values, and/or interesting relationships as drivers or covariates of pool depths.

About 60% of the variation in RBS was explained by the log of mobile mean substrate diameter at the time of each

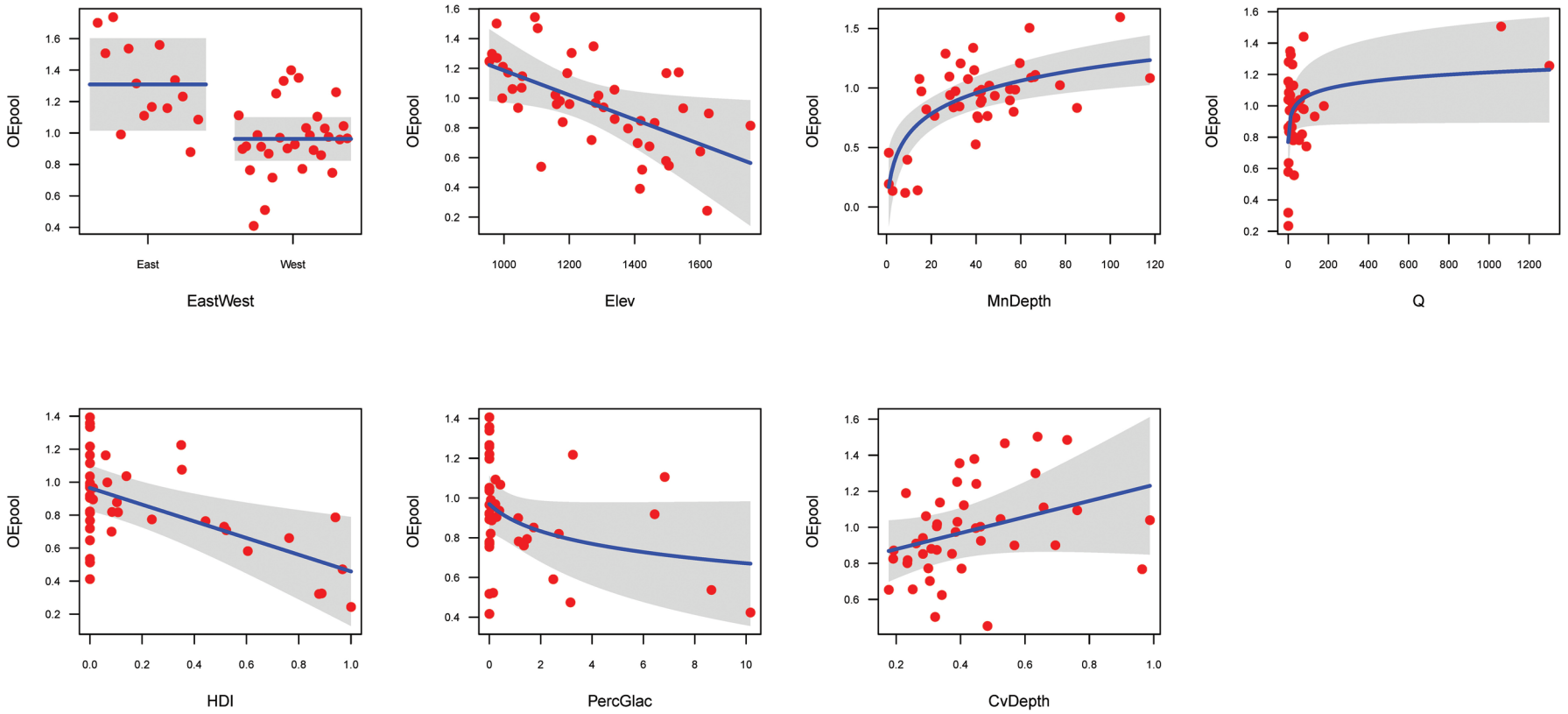


Figure 51. Partial residual plots of exploratory model of Glacier National Park ratio of observed to expected stream pool depths in 2007–2009. Conditional partial residuals show the relationship between each unique independent variable and the ratio of observed to expected pool depths, with all other variables held constant at the median for numeric variables and most common level for factors. All variables are shown back transformed to their original scale as applicable. Plots of numeric predictors include a best fit line and 95% confidence bands around this fit. Box plots of factorial variables include the reference category first, or on the leftmost side of the figure, and the 95% confidence interval as the bounding box around the variable's median. Codes in figures are: OEpool = observed to expected pool depth; EastWest = location of site relative to the continental divide; Elev = elevation (m); MnDepth = mean depth (cm); Q = discharge (m3/s); HDI = human disturbance index; PercGlac = percent of catchment as glacier; CvDepth = coefficient of variation in depth. See the full model results in Appendix F and Table 18.



Figure 52. Example of a stream in Glacier National Park with a naturally low ratio of observed to expected pool depths but with little human disturbance. This site is on a tributary to Lincoln Creek and also supports high quality biota, such as Rocky Mountain tailed frog tadpoles, *Ascaphus montanus* (inset). (FLATHEAD LAKE BIOLOGICAL STATION/ P. MATSON)

Table 19. Model of relative bed stability in 2007–2009 for streams in Glacier National Park. Final model selected using Akaike Information Criterion (AIC) and expert opinion from 22 candidate variables. Relative importance (Rel. Imp %) is the total amount of explained variance for each variable expressed as a percentage.

Model component	Estimate	SE	t	p	Rel. Imp. (%)
Intercept	-1.88	0.82	-2.30	0.03	–
East vs. west (west)	-0.88	0.21	-4.14	0.00	0.04
Human Disturbance Index	-0.71	0.21	-3.38	0.00	0.03
Elevation	-2.02E-03	5.15E-04	-3.91	0.00	0.04
% glacier in catch. (log)	-0.33	0.09	-3.73	0.00	0.14
Mobile mean substrate diameter (log)	0.64	0.07	9.77	0.00	0.60
Mean water depth (log)	0.47	0.09	5.31	0.00	0.13
Mean bankfull height (log)	-0.50	0.20	-2.43	0.02	0.02

Notes: SE = standard error of coefficient, t = t test value, p = probability of the t. Residual standard error: 0.30 on 16 degrees of freedom, Multiple R^2: 0.92, Adjusted R^2: 0.79, F-statistic: 7.19 on 25 and 16 DF, p-value: 8.277e-05

sample, with RBS increasing (tending towards armoring) with increasing mobile substrate diameters (Figure 53, Table 19). The smallest mobile sediments were associated with fining or sites with more small sediment than predicted given their geophysical context. Importantly, this is an expected relationship and reflects the construction of the RBS metric. The model also includes the log of mean water depth and mean bankfull height, with RBS lower in shallower streams and where bankfull heights are smaller (Figure 53, Table 19). Shallower streams with lower banks in Glacier tend to have less stream power and thus more fines than expected (Diplas et al. 2016; Eaton and Rosenfeld 2016). Conversely, sites with higher banks had larger substrates and tended more towards armoring. These three predictors were included in the model in order to control for their expected important covariance with RBS and other, perhaps more surprising, independent variables. While these attributes may be affected by human disturbance (i.e., water drawdown or fine sediment input from roads), we expect they are all largely naturally varying aspects of stream physical habitat in Glacier or only locally important and thus not an area of concern for the streams in the park.

With these likely natural sources of variation accounted for, we are left once again with our general metric of human disturbance, HDI (Figure 53, Table 19) as an explanatory variable for RBS. The relative importance of HDI was only 3%. However, this still may be an ecologically significant result at select sites as it suggests RBS tends towards fining where HDI is higher. RBS depends on both the supply of sediment and the capacity for sediment to be transported, thus there may be multiple possible connections to anthropogenic disturbances. Nevertheless few sites (largely the same impacted sites identified using other metrics) in Glacier have both RBS in a major (or nearly so) disturbance class and high HDI; we consider this result more of something to watch for than a concern for the park's streams in 2007–2009. Finally, the percentage of active glaciers in a site's catchment also tended to increase fining (elevation was also in the model, thus this is not confounded with high or low elevation streams). This is an interesting result and may reflect the increased contribution of fine sediments ("glacial flour") to streams in basins with more glaciers in their headwaters. However this is complex as it may also suggest that fining is the more natural state in many park streams. In general, the distribution of RBS in Glacier does tend more towards fining. This is a potentially important link to shifting climate regimes and thus an ongoing focus of work on streams in Glacier.

3.8 Bioassessment of ecological integrity

3.8.1 Summary condition

In general, bioassessment of the macroinvertebrate and diatom communities in Glacier in 2007–2009 indicated that streams were in a reference state, with high ecological integrity. Macroinvertebrate and diatom communities had a strong relationship with human disturbance; that is, the healthiest stream communities occurred in streams with no measurable human disturbance. Only a small percentage of stream in the park was in a non-reference state (usually in the front country). Few areas in Glacier showed issues with specific stressors (e.g., sediments or nutrients) as evaluated through bioassessment. Table 20 presents a summary condition of our bioassessment results. See the Executive Summary for a summary condition table of all Stream Ecological Integrity indicators together.

3.8.2 Overview

The majority of the results presented to this point in this report are largely in support of our estimation of the ecological integrity of the park's streams. In this chapter we present direct estimates of integrity using two important aquatic assemblages, macroinvertebrates (aquatic insects, worms, crustaceans, and other invertebrates) and algae (microscopic soft and hard bodied plants living in streams). Macroinvertebrates and algae are major components of the biodiversity found in streams. They are the base of the food web and thus support a broad range of other species. They are excellent indicators of ecological integrity because of their ability to integrate different processes and because they respond to physical, chemical, and biological disturbances at multiple temporal and spatial scales. Resh (2008) suggests that surveying macroinvertebrates is one of the most efficient ways to monitor streams over the long term and macroinvertebrates are the most widely used group for biological monitoring of streams and rivers around the world (Bonada et al. 2006). For algae we focus on diatoms (single celled hard bodied alga with cell walls made of silica). Diatoms play important roles in the processing of CO2, O2, carbon, and silica in streams, among many other important ecological services. They are excellent biomonitors in a wide range of aquatic ecosystems (Stevenson and Smol 2003) because of their diversity, population sizes, short generation times, and high fidelity to specific ecological conditions. Using both macroinvertebrates and diatoms is advantageous as each estimates different scales and types of ecological response to disturbance in the park's streams.

The assessment of biological data from stream monitoring has a rich history – even its own name "bioassessment."

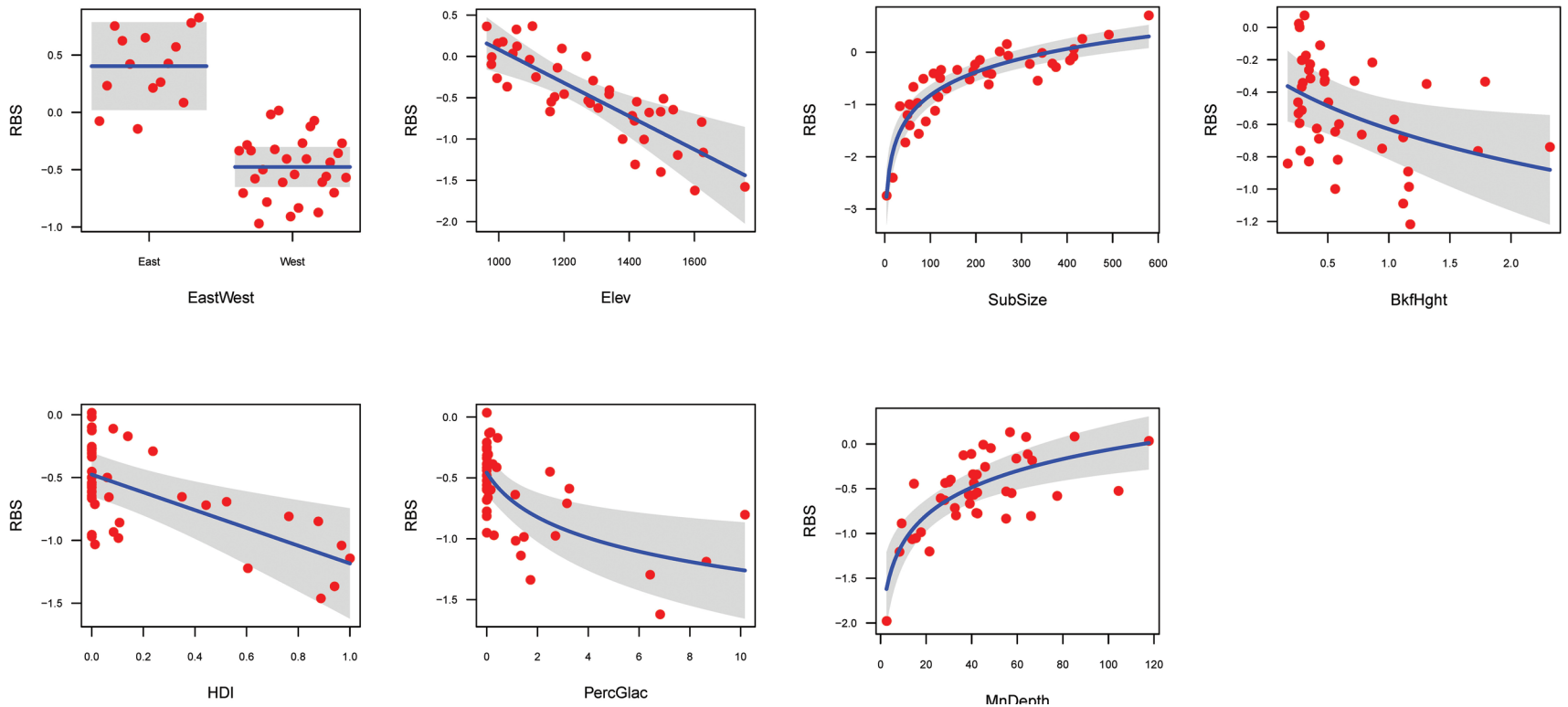
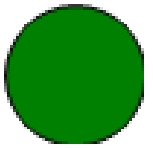


Figure 53. Partial residual plots of exploratory model of Glacier National Park relative bed stability (RBS) in 2007–2009. Conditional partial residuals show the relationship between each unique independent variable and RBS with all other variables held constant at the median for numeric variables and most common level for factors. All variables are shown back transformed to their original scale as applicable. Plots of numeric independent variable include a best fit line and 95% confidence bands around this fit. Box plots of factorial variables include the reference category first, or on the leftmost side of the figure, and the 95% confidence interval as the bounding box around the variable's median. Codes in figures are: RBS = relative bed stability; EastWest = location of site relative to the continental divide; Elev = elevation (m); SubSize = mean substrate size (mm); BkfHght = bankfull height (m); HDI = human disturbance index; PercGlac = percent of catchment as glacier; MnDepth = mean depth (cm). See the full model results in Appendix F and Table 19.

Table 20. Summary condition table for bioassessment of macroinvertebrates and diatoms at Glacier National Park in 2007–2009. We structure the table by indicators of stream ecological integrity (SEI). We include the types of assessment points used, a brief description of key results, and symbolize the status and our confidence in these summaries. Key to the condition and confidence symbol: red color = non-reference condition/major disturbance, yellow color = intermediate condition/moderate disturbance, dark green color = reference condition/minor disturbance, light green color = pristine reference condition/negligible disturbance, no color = unknown or indeterminate; upward arrow = condition is improving, sideways arrows = condition is unchanging, downward arrow = condition is deteriorating, no arrow = unknown trend; heavy border = high confidence, regular border = medium confidence, dashed border = low confidence. Table 5 offers a visual key. For a condensed version of these results, see the summary condition table in the Executive Summary.

Indicator	Condition description	Condition and confidence
Overall stream ecological integrity	Based on an analysis of stream macroinvertebrate and diatom communities, the ecological integrity of Glacier's streams was mostly excellent, with the majority of the park's streams in a reference or pristine reference condition in 2007–2009. Macroinvertebrate and diatom communities were largely intact and sometimes included previously undescribed species, suggesting a high level of biological distinctiveness in the park. Localized impacts to these communities from sediments, nutrients, or metals were minor. Front country streams, including tributaries to the North Fork of the Flathead, Rubideau Creek near park headquarters, Divide Creek near St. Mary, and Railroad Creek near East Glacier had reduced condition, with a likely human disturbance cause. We have medium to high confidence in our overall assessment given generally acceptable signal in the data, relevant ecological thresholds, and ecoregion baseline bioassessment points for many metrics. We are especially confident that our results will be useful baselines for understanding changes over time, given the high quality design, data, and modeling we employ. *There was some indication in our models that climate driven effects could be important to stream biota. Data from partners suggest this might be especially important for temperature sensitive species like the meltwater stonefly.*	
Macoinvertebrate and diatom communities – bioassessment models	We used models of macroinvertebrate and diatom community condition, including custom tools scaled to the park that account for the role of natural drivers for bioassessment. We also applied established methods from Montana DEQ. It is useful to include both of these approaches in our assessment because they tend to show similar patterns in condition across the park's streams as a whole and at specific sites. Given the synthetic nature of these models, we consider these results our best evidence for the high ecological integrity of the park's streams. Around 70% and 54% of the streams in the park, based on park-scaled macroinvertebrate and diatom models (respectively), were in a reference or pristine reference condition. Pristine reference suggests there is no measurable human disturbance and an exceptional community composition. A small percentage of streams with issues likely linked to human disturbance occurred in the front country. The pattern in these results across the park resembled the distribution of human disturbance, several water chemistry measures above their non-reference assessment point concentrations, and select physical habitat metrics that exceeded reference levels. This may support a structural relationship between these drivers and ecological response. In general, lower integrity occurs on the boundaries of the park and along visitor services corridors. In particular, sites with lower integrity included Railroad Creek tributary site, the trio of tributaries to the North Fork of the Flathead (Big Creek, Coal Creek, and Canyon Creek), and Divide Creek on the park's east border. Some of these streams have historical and ongoing Clean Water Act listings by Montana DEQ for various human caused disturbances. We have strong confidence in our custom multimetric index (MMI) models that score sites as in a pristine reference class. These designations correspond to streams with no measurable human disturbance – a condition that we consider ecologically meaningful and well connected to the Glacier General Management Plan. Overall we have high confidence in our assessment for these parameters given generally acceptable signal in the data, relevant ecological thresholds, and ecoregion baseline assessment points for many metrics. We are especially confident that our results will be useful baselines for understanding changes over time, given the high quality design, data, and modeling we employ.	

Table 20 (continued). Summary condition table for bioassessment of macroinvertebrates and diatoms at Glacier National Park in 2007–2009. We structure the table by indicators of stream ecological integrity (SEI). We include the types of assessment points used, a brief description of key results, and symbolize the status and our confidence in these summaries. Key to the condition and confidence symbol: red color = non-reference condition/major disturbance, yellow color = intermediate condition/ moderate disturbance, dark green color = reference condition/minor disturbance, light green color = pristine reference condition/ negligible disturbance, no color = unknown or indeterminate; upward arrow = condition is improving, sideways arrows = condition is unchanging, downward arrow = condition is deteriorating, no arrow = unknown trend; heavy border = high confidence, regular border = medium confidence, dashed border = low confidence. Table 5 offers a visual key. For a condensed version of these results, see the summary condition table in the Executive Summary.

Indicator	Condition description	Condition and confidence
Macroinvertebrate and diatom communities – stressor specific models: sediment, nutrient, temperature, and metals	We directly link macroinvertebrate and diatom response to important specific stressors in Glacier using existing Montana DEQ models. These assessments may be more diagnostic and potentially useful for resource management in the park. There was some suggestion that macroinvertebrate response to nutrients had a possible connection to human disturbance. Around 30% of the park's streams were above a Montana DEQ threshold for macroinvertebrate response to nutrients. However SEI methods do not quite match the protocol required by the state to implement this assessment point, and given the general lack of non-reference response in other macroinvertebrate metrics, we treat this response with caution. Macroinvertebrate response to sediment likely reflects natural patterns. Montana DEQ models show a small response to sediment, nutrients, and metals in diatom communities and some of these streams were influenced by human disturbance that may have elevated concentrations. We have medium confidence in our assessment for these parameters. Some models may not be well calibrated to the scale of the park and we lack well distributed ecoregional reference sites from which baseline assessment points may be derived. *Of note, a metric based on macroinvertebrate response to water temperature indicates few of the park's streams are currently warmer than comparable ecoregional reference sites. However, because macroinvertebrate communities tolerant of colder water are strongly associated with higher ecological integrity, ongoing bioassessment will be important as the climate continues to warm.*	
Aquatic invasive species	Aquatic invasive species can have a strong effect on stream ecological integrity and are a focus of park resource management. We did not detect zebra mussel (*Dreissena polymorpha*), quagga mussel (*Dreissena rostriformis bugensis*), rusty crayfish (*Faxonius rusticus*), or New Zealand mudsnails (*Potamopyrgus antipodarum*) in our 2007–2009 data (or in any sentinel site data since). Given detections in 2016 of mussels in water samples from reservoirs near the park, and confirmed mudsnail populations in northwest Montana, we will closely watch for these and other invasive species in future monitoring. We found the invasive but native diatom *Didymosphenia geminata* (didymo) in a large portion of the park's streams, often in a bloom state. Research is ongoing on the implications of this to the park's streams and their management. Repeating the parkwide survey will be important for better understanding patterns in didymo distributions across the park. We have low to medium confidence in our assessment for these parameters given dated data and designs not optimized for early detection of invasive taxa. Moreover we lack quantitative assessment points for didymo (other species have a reference condition assessment point of no occurrences and thus, as of 2009, the park was in a reference state for these taxa). We documented simple presence/absence of five aquatic invasive species (not including fish) and our survey design does not target stream sites with high invasion probabilities. Therefore, this assessment should be used to understand long-term status of aquatic invasive species across the streams of Glacier and not as a management tool (e.g., for the exclusive identification of potential treatment areas or invasion "hot spots"). *Of note, didymo has complex relationships with nutrients and hydrology. Some research suggests it is connected to patterns driven by climate change and thus warrants careful monitoring.*	

Bioassessment is, generally speaking, the use of measures of the biological community to assess and monitor natural systems (Barbour et al. 2000) and is the primary way we address objectives focused on estimating status in the condition (or ecology integrity) of Glacier's streams. The process we use for bioassessment follows the hierarchy given in the assessment section 2.4.4.2, above, with any details specific to biological metrics clarified in Appendix D.

3.8.2.1 Macroinvertebrate and diatom diversity

To maximize our estimates of diversity we present summaries from all sample events across all site types and sample events in 2007–2009. Diatoms were almost always identified to species, while the most refined level for macroinvertebrates was a mix of species/genera and higher level operational taxonomic units (OTU; Jessup et al. 2006; Montana DEQ 2012a). In all cases, non-species level identifications were included in analyses only if we had confidence that the taxon was consistent and unique across all samples.

From 2007 to 2009 we collected and identified 343 unique macroinvertebrate taxa (of varying levels of identification), 529 diatom taxa (most are species), and 65 soft bodied algae taxa (of varying levels of identification; Appendix G gives complete taxa lists). Mean average taxa per site was 44.8 for diatoms and 48.6 for macroinvertebrates (Table 21). Mean Shannon diversity (taxa counts weighted by their relative abundance) was 3.7 and 3.8 for diatoms and macroinvertebrates, respectively. Shannon diversity is generally between 1.5 and 3.5 in most ecological studies, and the index is rarely greater than 4. The Shannon index increases as both the richness and the evenness of the community increase. Glacier diversity measures are typical of taxa rich assemblages with a pronounced inverse J curve in species accumulation, indicating that many sites have a few species with high relative abundances, and a longer list of taxa with low relative frequencies of occurrence across sites.

In qualitative comparisons to EMAP data from the Northern and Canadian Rockies (Stoddard et al. 2005), the diversity of Glacier's macroinvertebrate community was high. Across all sites the population scale mean diversity for Glacier was 3.07; for ecoregion reference sites the site level average was around 2.8. Shannon index typical values are generally between 1.5 and 3.5 in most ecological studies and the index is rarely greater than 4 (a community with only one species would have a value of 0). The World Wildlife Fund rates the biological distinctiveness of the Canadian Rockies Ecoregion as "Continentally Outstanding" (Abell et al. 2000). Much of the Pacific Northwest, within which the Canadian Rockies lies, was heavily glaciated during the Pleistocene and as a result has few known endemic aquatic species. However, the Canadian Rockies Ecoregion served as a refugium for freshwater species during the last glaciation, and as a result the region supports a number of endemic fish and invertebrates (Abell et al. 2000). Glacier, at the headwaters of three continental drainages, protects and provides clean water and high quality aquatic habitats for these species.

Stanford et al. (1994) describe the macroinvertebrate assemblages of the park as very species rich, owing in part to the pristine, oligotrophic nature of the waters and the wide variety of aquatic habitats along the altitudinal gradient. Moreover, because the park exists midway in the north–south continuum of the Rocky Mountains, and three major river systems of the North America continent share adjacent headwaters, many species are on the fringe of their continental distribution and the area serves as a "melting pot for biodiversity." For example, 67% (101 species) of Plecoptera (stoneflies) reported for the Rocky Mountains from Alaska to New Mexico have been collected in the Flathead catchment.

The diatom assemblage in Glacier is thought to be one of the more diverse known (Spaulding et al. 2010). If lakes, wetlands, seeps, and other standing water habitats are included, along with flowing waters, the total number of recognized diatom species in the park is likely well over 1,000 (L. Bahls, pers. comm., 2012). Historically, the most completely studied country (for diatoms) is Germany, where 1632 species have been reported. Therefore, Glacier, which is of course much smaller (Glacier is 1.5% the size of Germany) and lacks estuarine and brackish water habitats, has at least two-thirds the number of diatom species. Importantly there is a sampling intensity effect here, with other remote and previously unexplored regions of the world having comparable diatom diversity when sampled as thoroughly as Glacier (e.g., Finland, Madagascar, Sardinia, the Andes, Arctic Canada).

Table 21. Summary of diversity indices for macroinvertebrates and diatoms monitored at Glacier National Park, 2007–2009. Diversity is estimated using the Shannon index (Shannon 1948).

Indicator	Total taxa richness	Total Shannon diversity	Mean taxa richness	Mean Shannon diversity
Diatoms	529	5.32	44.80	3.72
Macroinvertebrates	343	5.20	48.60	3.86

3.8.2.2 Community structure in relation to key drivers

Ordination and clustering models were used to better understand patterns between macroinvertebrate and diatom community structure (separately) and key environmental variables. In community analysis, classification assigns sites into classes or groups, whereas ordination arranges sites, sometimes together with species, along gradients. Both techniques have a long standing tradition in ecology. We limit the amount of statistical content presented here, as we treat these models as largely useful background and conceptual support for subsequent bioassessment modelling. Appendix D provides methodological details.

Macroinvertebrates

Our ordination of the macroinvertebrate data resulted in a two dimensional solution that represented approximately 54% of the variance in the distance matrix. We reduced 43 candidate environmental gradients to 11 based on the strength of correlation with the model, significance, ecological uniqueness, and their general interpretability (Figure 54, Table 22). The agglomerative coefficient measuring the qual-

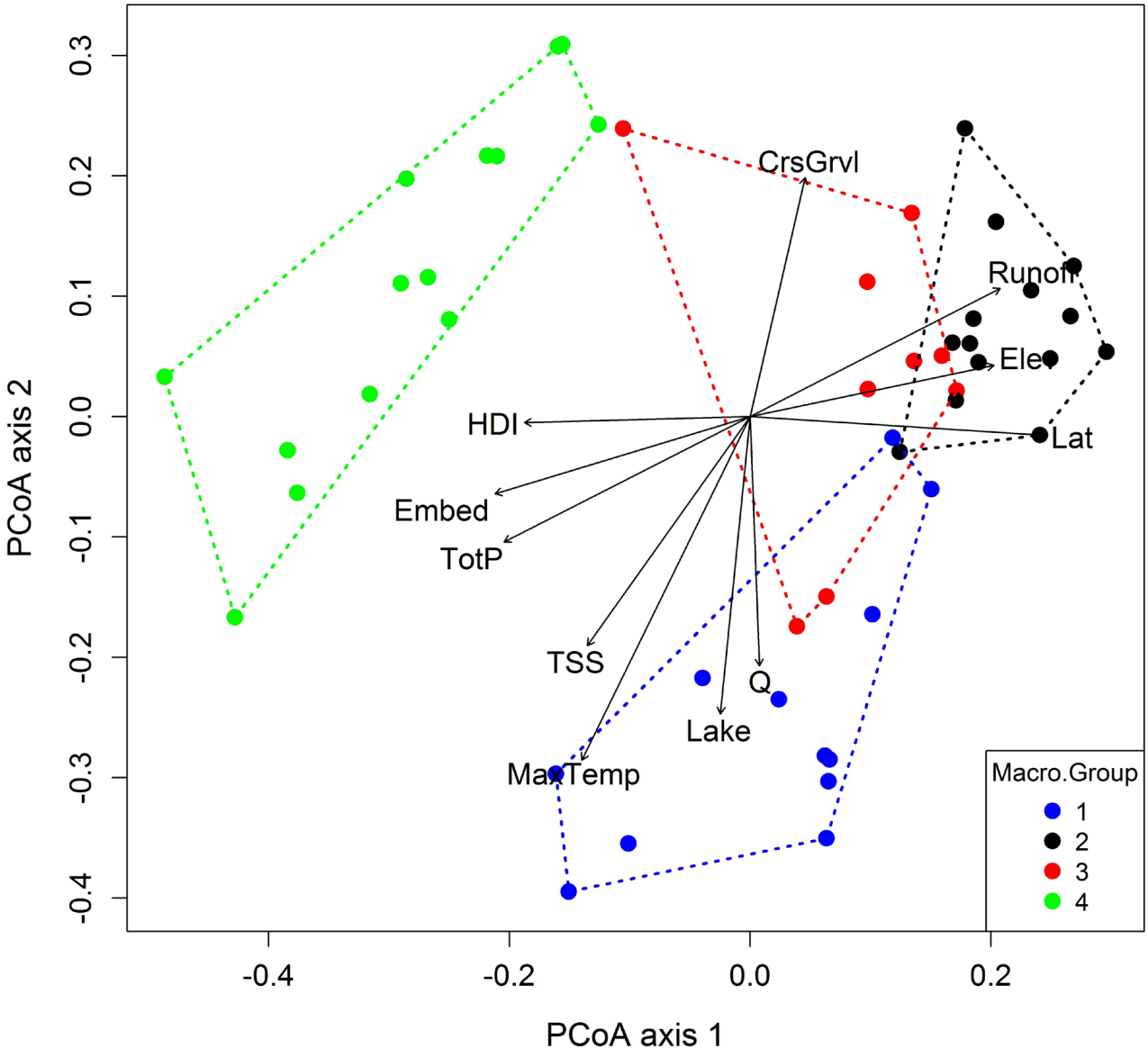


Figure 54. Principal Coordinates Analysis (PCoA) ordination of macroinvertebrate communities at stream sites in Glacier National Park, 2007–2009. Vectors show important environmental covariates with Bonferroni corrected p-values less than 0.05. CrsGrvl = percent coarse gravel; Runoff = mean annual predicted runoff; Elev = elevation (m); Lat = site latitude; Q = instantaneous discharge; Lake = distance to closest lake; MaxTemp = maximum stream temperature in catchment; TSS = total suspended sediments; TotP = total phosphorous; Embed = mean embeddedness; HDI = Human Disturbance Index. Polygons group sites by cluster based groups of macroinvertebrates (Macro Group 1 - 4).

Table 22. Macroinvertebrate principal coordinates ordination at stream sites in Glacier National Park, 2007–2009. Eleven environmental variables were included based on the strength of their correlation, significance, and their overall interpretability. PCoA 1 and PCoA 2 = location of the vector on first and second axis, r^2 = coefficient of determination, p = significance of each variable (via simulation). Variable name is followed by its short name as used in the ordination plot (Figure 54).

Variable	PCoA 1	PCoA 2	r^2	p
Maximum stream temperature in catchment (MaxTemp)	-0.334	-0.415	0.425	0.000
Distance to closest lake (Lake)	-0.127	-0.292	0.259	0.001
Site Latitude (Lat)	0.366	-0.029	0.255	0.002
Mean annual predicted runoff (Runoff)	0.350	0.095	0.229	0.002
Total suspended sediments (TSS)	-0.169	-0.186	0.229	0.002
Total Phosphorous (TotP)	-0.310	-0.007	0.221	0.002
Mean embeddedness (Embed)	-0.292	-0.076	0.206	0.003
Instantaneous discharge (Q)	0.019	-0.261	0.180	0.008
Site elevation (Elev)	0.310	0.007	0.180	0.010
Percent coarse gravel (CrsGrvl)	0.104	0.140	0.175	0.013
Human Disturbance Index (HDI)	-0.299	-0.204	0.148	0.024

ity of the initial clustering was 0.94, suggesting that a clear structuring in the macroinvertebrate community was found in our data. The goodness of fit (54%) was acceptable given the high degree of natural variability in macroinvertebrate community structure.

The first axis ("PCoA axis 1" in Figure 54) describes a contrast between gradients in elevation, latitude and mean annual runoff on its positive side, and HDI, embeddedness, and total phosphorous concentration on its negative end. This matches intuitive patterns in stream type. On the positive (right) side of the axis, high elevation streams with high runoff per unit watershed area contrast with low elevation sites with higher levels of human disturbance, embedded substrates, and nutrient concentrations on the negative (left) side. Macroinvertebrate community structure clearly responded to this contrast in environmental drivers, with a fairly tight association of groups 2 and 3 on the positive end of this axis and in a less focused group 4 on its negative end. Group 4 also spanned the gradient across the second dimension of the PCoA. This axis ("PCoA axis 2" in Figure 54) was a contrast between coarse gravel and (to a lesser degree) mean annual runoff on its positive end and total suspended sediments, distance to closest lake, discharge, and the maximum stream temperature in the site's catchment on its negative side. Again this contrast makes ecological sense, with stream sites dominated by finer substrates more affected by lake outlets, higher discharge, and warmer maximum temperatures. Macroinvertebrate group 1 mapped tightly with the negative end of this axis. Group 4 was arrayed more along the continuum of this axis. These patterns in community structure create spatially distinct groups across our sites in the park (Figure 55).

Diatoms

Ordination resulted in a two dimensional solution that represented approximately 48% of the variance in the distance matrix. We reduced 60 candidate environmental gradients to 11 based on the strength of correlation with the model, significance, ecological uniqueness and their general interpretability (Figure 56, Table 23). The agglomerative coefficient measuring the quality of the initial clustering was 0.92, suggesting that a clear structuring in the diatom community was found in our data. However, the goodness of fit for the PCoA (48%) was lower than ideal but generally acceptable given the high degree of natural variability in diatom community structure. Diatoms may be arranged more continuously across the gradient of community types than macroinvertebrates, leading to a less distinct patterning in the ordination. Their community structure also responds to changes in their environment much more quickly than macroinvertebrates, and some of our environmental variables may not be measured on a time scale matching the variance in diatom community composition.

The four diatom groups were distinguished by some of the same environmental variables as in the macroinvertebrate's ordination, although the patterning was not as clear (i.e., diatom groups were less clustered and the environmental gradients less orthogonal with one another). The first axis ("PCoA 1" in Figure 56) was characterized by gradients in fine gravel, distance to closest lake, maximum stream temper-

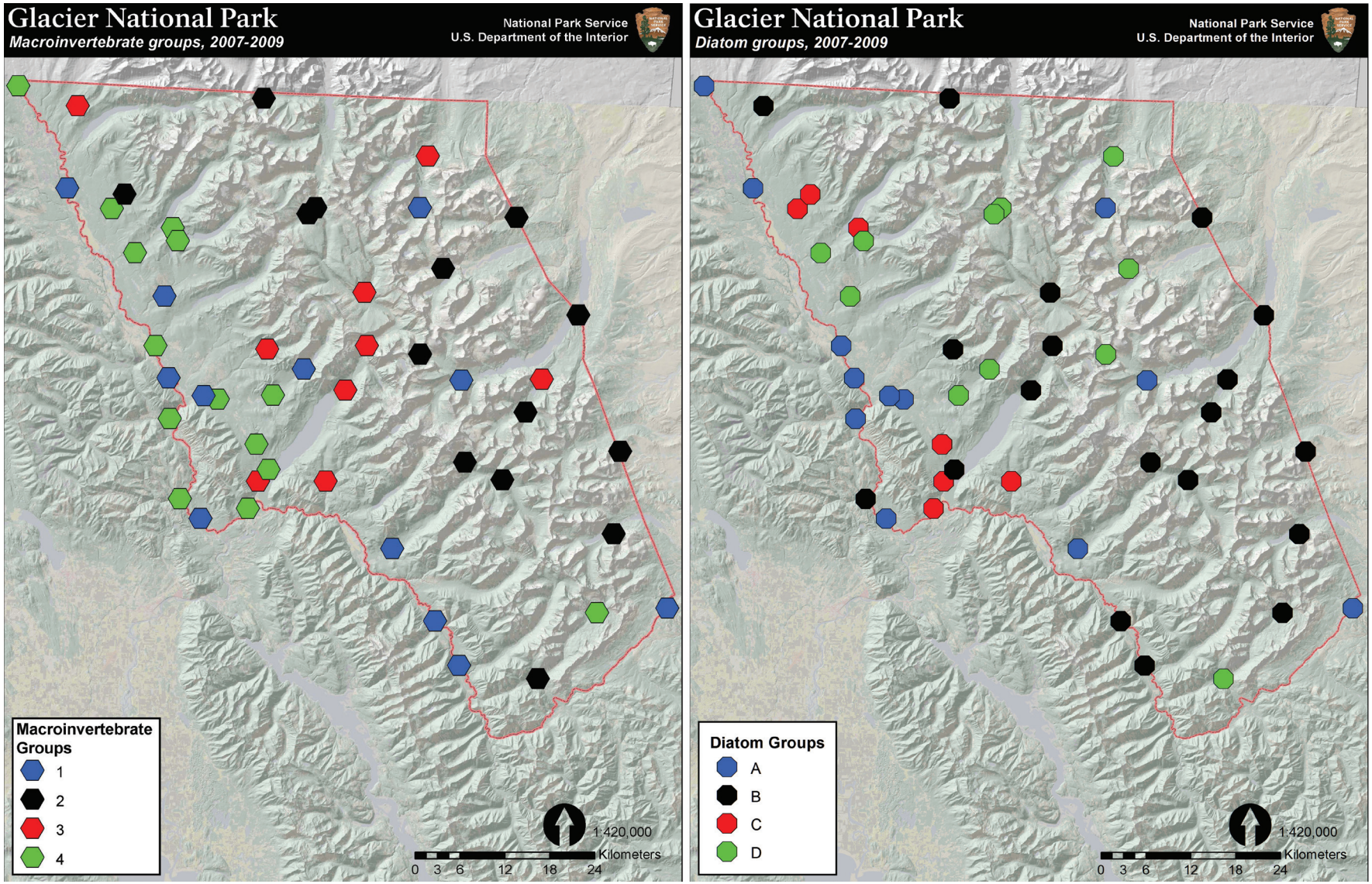


Figure 55. Map of macroinvertebrate (left panel) and diatom groups (right panel) at Stream Ecological Integrity sites in Glacier National Park, 2007–2009. Groups are based on a cluster model. See Appendix A for a complete list of site numbers and names.

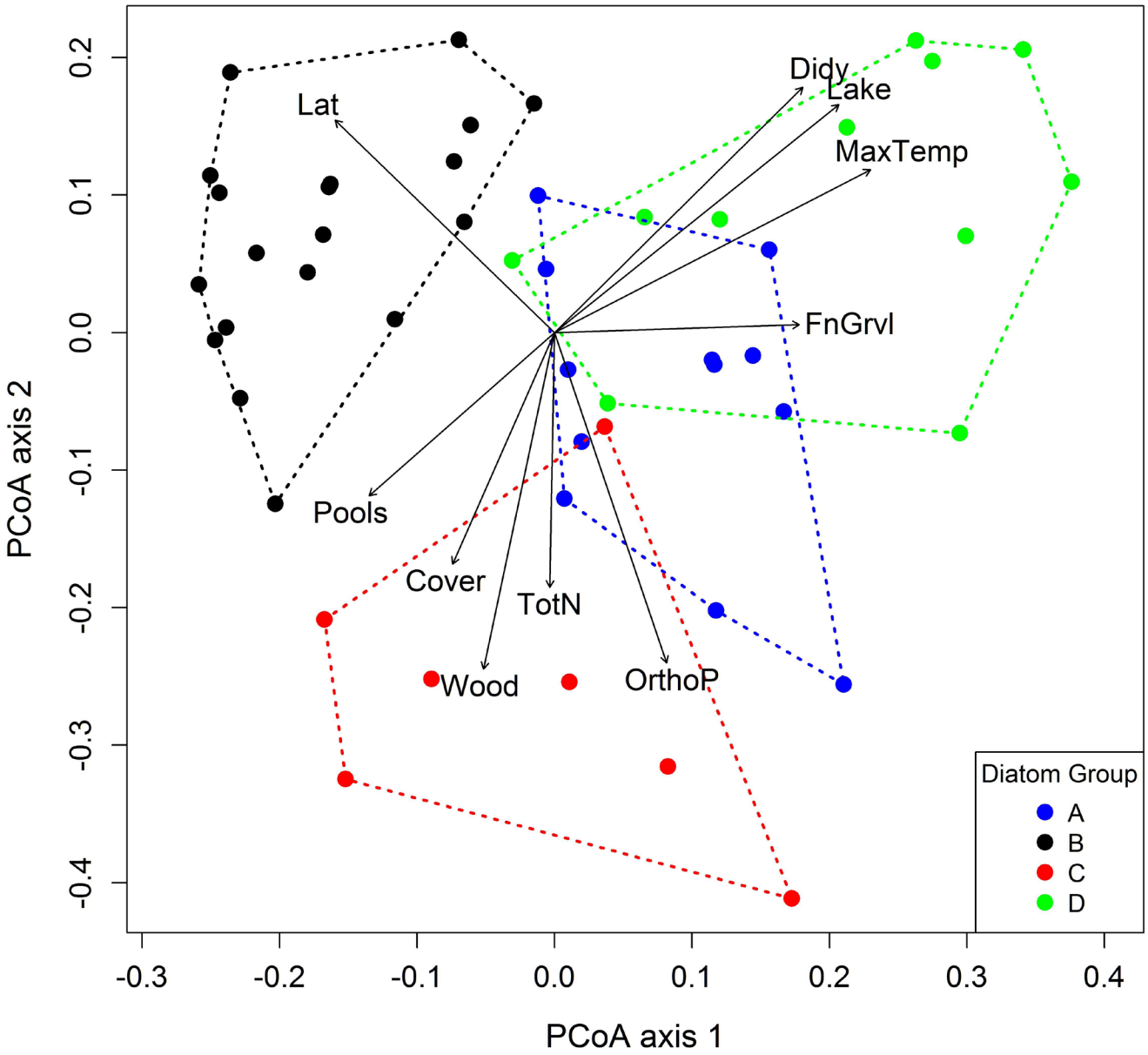


Figure 56. Principal Coordinates Analysis (PCoA) ordination of diatom communities at stream sites in Glacier National Park, 2007–2009. Vectors show important environmental covariates with Bonferroni corrected p-values less than 0.05. Didy = Didymosphenia index; Lake = distance to closest lake; MaxTemp = maximum stream temperature in catchment; FnGrvl = percentage of fine gravel; OrthoP = orthophosphate concentration; TotN = total nitrogen concentration; Wood = total wood volumne; Cover = bank vegetation; Pools = pool density; Lat = site latitude. Polygons group sites by cluster based groups.

ature in the site's catchment, and an index of didymo abundance on its positive end (although these last three variables were not exclusively related to this dimension of the ordination). The opposite side of axis 1 was marginally associated with pool density. Otherwise it did not have a strong association with gradients in our model, so it is best interpreted as the opposite of the four variables on its positive end (i.e., low fine gravel cover, cold maximum temperatures, less didymo, and sites well away from lakes). The associations among distance to closest lake, maximum stream temperature, and didymo abundance are important given the possible effects of didymo on stream condition (Schweiger et al. 2011) and as suggested by this model, diatom community structure. Didymo, with often extensive blooms that alter the physical structure of a stream, in this context may be considered an environmental gradient (e.g., we do not feel it is circular). Diatom groups D and A were somewhat loosely associated with the positive side of axis 1, with A also arranged along

Table 23. Diatom principal coordinates ordination at stream sites in Glacier National Park, 2007–2009. Eleven environmental variables were included based on the strength of their correlation, significance, and their overall interpretability. PCoA 1 and PCoA 2 = location of the vector on first and second axis, r^2 = coefficient of determination, p = significance of each variable (via simulation). Variable name is followed by its short name as used in the ordination plot (Figure 56).

Variable	PCoA 1	PCoA 2	r^2	p
Distance to closest lake (Lake)	0.22	0.29	0.30	0.00
Maximum stream temperature in catchment (MaxTemp)	0.39	0.14	0.28	0.00
Didymo index (Didy)	0.28	0.24	0.27	0.00
Orthophosphate concentration (OrthoP)	0.11	-0.27	0.27	0.00
Total wood volume (Wood)	-0.03	-0.24	0.27	0.00
Site Latitude (Lat)	-0.26	0.20	0.21	0.00
Total nitrogen concentration (TotN)	-0.05	-0.08	0.15	0.02
Bank vegetation (Cover)	-0.11	-0.13	0.14	0.03
Pool density (Pools)	-0.21	-0.07	0.14	0.03
Percentage of fine gravel (FnGrvl)	0.25	-0.06	0.14	0.04
Embeddedness (Embed)*	0.17	-0.21	0.11	0.06

*Note embeddedness does not plot on the ordination in Figure 56, given its marginal significance.

axis 2. Group B occurred on the negative side of axis 1, with most sites in the North Fork of the Flathead drainage (Figure 55). The second axis ("PCoA 2" in Figure 56) was described by bank vegetation, total nitrogen, orthophosphate concentration and total wood volume on its negative end. The positive side of the second axis was characterized by latitude and to a lesser extent, distance to closest lake, maximum stream temperature in the site's catchment and didymo abundance. Diatom group C was associated with the negative side of axis 2, with most sites in the North Fork of the Flathead drainage. Diatom group B (also in this same drainage) was on the positive side of axis 2, suggesting an interesting pattern across these environmental gradients on the west side of the park. Both of these groups also were arrayed along axis 1 to a lesser degree.

From ordination to bioassessment

There is some qualitative similarity in how the two ordinations partition stream type across the park (see Figure 55). There was a degree of correspondence between site membership in the macroinvertebrates and diatom groups, but it is clear that the two assemblages are structured by several different gradients – in part, this is why we monitor two biological assemblages. The primary purpose of bioassessment is to detect and measure impact and resultant condition, rather than to differentiate sites or recognize major environmental gradients, as done in species ordination. However ordination provides useful background and context for better understanding why we might see a certain community composition in a stream.

Our ordination revealed strong associations between macroinvertebrate community structure and environmental gradients classically associated with macroinvertebrate–habitat relationships. Human disturbance was also an important potential driver and may be associated with sediments and nutrients. These patterns are useful as support for bioassessment models. Likewise the associations between diatom community structure and environmental gradients were interpretable, although patterns were less pronounced or clear than in the macroinvertebrate community. Nevertheless, the environmental gradients in the models include many that drive diatom–habitat relationships in other systems, especially sediment and nutrients, and are useful in better understanding this assemblage in Glacier and in support of bioassessment models. However, no human disturbance variables were in the final diatom model (several were reviewed as candidate metrics).

3.8.3 Ecological integrity: detailed results and interpretation

The following sections present results and interpretation of bioassessment models for macroinvertebrates and diatoms at SEI sites sampled in 2007–2009. Results focused on patterns over time (change and trend) are presented in our sentinel site report (Schweiger et al. in preparation a).

3.8.3.1 Macroinvertebrates

Table 24 provides summaries of macroinvertebrate bioassessment results, including park-scaled models developed for this report and existing large scale bioassessment models estimated using SEI data. These models are summarized and discussed in turn in the following sections.

Table 24. Summary of six macroinvertebrate-based bioassessment metrics in Glacier National Park, 2007–2009.

Category	Habitat indicator	Change with decrease in ecol. condition	Min. value from survey sites (all sites)	Park scale median	Max. value from survey sites (all sites)	LCL	UCL	Assessment points			Assess. point type	% of park streams in stressor class				Signal to Noise ratio (S:N)
								Major	Minor	Negligible		Major	Moderate	Minor	Negligible	
ROMN	Glacier Macroinvertebrate MMI (MMI_{Gm})	Dcr	3.49 (3.13)	5.46	6.78	5.13	5.99	<3.86	5.18	>5.76[1]	ERG*	9.9	23.1	19.0	47.6	1.6
Montana DEQ	RIVPACS O:E (2005 model; p > 0)	Dcr	0.45	1.0	1.46 (1.53)	1.0	1.10	<0.56	>0.96[2]	–	ERG	9.9	16.9	73.2	–	0.35
Montana DEQ	RIVPACS BC (2005 model; p > 0)	Inc	0.40	0.5	0.77	0.46	0.55	>0.71	<0.59[2]	–	ERG	5.2	23.5	71.3	–	3.09
Stressor specific	Fine Sediment Biotic Index	Dcr	1.73	4.8	5.83	4.5	4.88	<2.78	>4.26[2]	–	ERG	11.7	19.7	68.6	–	3.59
Stressor specific	Temperature Index	Inc	10.43	11.8	17.93	11.33	13.32	>15.22	<13.54[2]	–	ERG	3.3	22.1	74.6	–	7.10
Stressor specific	Hilsenhoff Biotic Index (nutrients)	Inc	1.24	3.4	7.16	3.17	4.07	>4.0[3]	–	–	THR	30.3	–	69.7	–	1.23

Table Notes: Median and confidence intervals are derived from survey-design based estimation methods. Minimums and maximum values are at the site scale and (if meaningfully different) given for survey only sites and (in parentheses) all sites. RIVPACS = River Invertebrate Prediction and Classification System, O:E = Observed to expected ratio, BC = Bray Curtis dissimilarity index. Codes for assessment point types are: THR = ecological threshold; ERG = ecoregional; ERG*= ecoregional assessment point plus an HDI = 0 predicted Glacier Macroinvertebrate MMI assessment point. Note that where there is only one assessment point, there is no moderate class and we therefore lump moderate and minor categories and apply the color code from the minor class. The percentage of Glacier National Park streams in major/moderate/minor stressor classes were derived by comparing design-based results to assessment points. Some percentages are approximate as assessment points often fell between two values in the cumulative distribution and had therefore to be interpolated. S:N was derived across all 49 sites and the 97 visits to these sites from 2007 to 2009. Problematic S:N values are below 1.0.

[1] Ecoregional assessment points predicted from a model of Glacier Macroinvertebrate MMI and HDI and a >95th percentile HDI value for major disturbance and a <75th percentile HDI for minor disturbance (a moderate disturbance class falls in between these values). For the negligible disturbance class, we use the predicted value at HDI = 0.

[2] Ecoregional assessment points generated from reference sites in the Northern and Canadian Rockies Ecoregion, including Glacier National Park (Stoddard et al. 2005, 2006). For responses that decrease with decreasing condition, we use the <5th percentile for major disturbance and a >25th percentile for minor disturbances or a reference condition. For responses that increase with decreasing condition, we use the >95th percentile for major disturbance and a <75th percentile for minor disturbances.

[3] State of Montana aquatic life support standards (Montana DEQ 2012b, 2017)

Glacier National Park Macroinvertebrate Multimetric Index (MMI_{Gm}*): Estimation*

We construct a macroinvertebrate multimetric index specific to Glacier National Park (hereafter, Glacier Macroinvertebrate MMI, or MMI_{Gm}; Table 24) from a model of a set of 107 candidate macroinvertebrate metrics (Appendix D), HDI, and a suite of environmental covariates (Figure 57) following Schoolmaster, Grace, and Schweiger (2012), Schoolmaster, Grace, et al. (2012), and Schoolmaster et al. (2013).

Human disturbance to streams in Glacier has a complex and multivariate effect. Therefore it is this multivariate relationship with disturbance that needs to be evaluated and incorporated into MMI construction. In practice, this means selecting sets of metrics based on how they respond to disturbance as a group, as opposed to how each metric responds individually (as is done in more classic MMI models; i.e., Karr and Kerans 1994; Jessup et al. 2006). Schoolmaster, Grace, and Schweiger (2012) and Schoolmaster, Grace, et al. (2012) show that the characteristics of metrics that will combine to produce the most sensitive MMI cannot be deduced from the bivariate relationships between the metrics and human disturbance. Instead, whether a candidate metric improves the sensitivity of a MMI (or not) depends on the strength of the disturbance signal in the candidate metric and its unique explanatory power within a set of candidate metrics. We incorporate the way that metrics combine to convey information about disturbance into the construction of the Glacier Macroinvertebrate MMI for Glacier's streams.

We consider environmental covariates to be relevant in the Glacier Macroinvertebrate MMI (Figure 57) if they have demonstrated relationships with macroinvertebrate response in the literature and/or in our analyses of SEI Glacier data

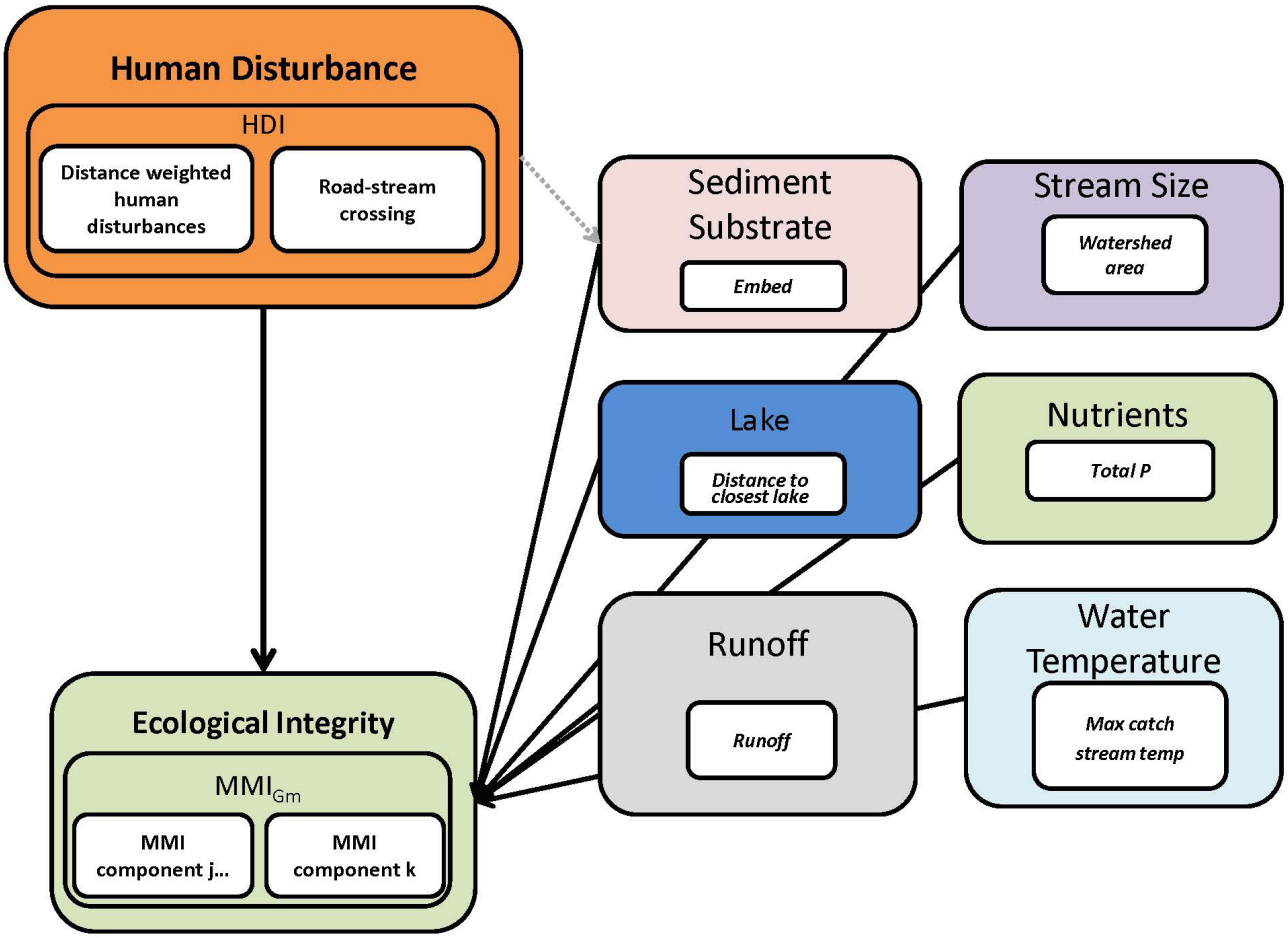


Figure 57. Conceptual model for Glacier Macroinvertebrate Multimetric Index (MMI_{Gm}). Covariates included in model are shown with solid boxes/arrows, with the assumed or demonstrated structural direction of a relationship indicated by the head of an arrow. Dotted faint arrow indicates possible structural connection between HDI and an environmental gradient but one that we assume plays a minor role in Glacier.

(see the human disturbance, water chemistry, and physical habitat sections above) – but not human disturbance. Following Schoolmaster, Grace, and Schweiger (2012) and Schoolmaster, Grace, et al. (2012), where disturbance meaningfully influences an environmental gradient, adjusting for the gradient within the Glacier Macroinvertebrate MMI removes part of the effect of human disturbance (and therefore such a gradient is not a good candidate for the modeling process). Our final model (Figure 57) includes six covariates, each of which influences stream macroinvertebrates. Of these, watershed area and distance to closest lake clearly have no causal relationship with human disturbance. Maximum water temperature and runoff have complex, largely indirect, structural relationships with human disturbance, but they likely unfold over long time and spatial scales. In other systems, human disturbance can play a strong role in nutrient concentration; however, our model of total phosphorous SEI data did not reveal any statistical connections between HDI and this important nutrient in Glacier in 2007–2009. HDI can influence stream substrates, including embeddedness. We do not model embeddedness specifically in Glacier. Our predictive model of relative bed stability (correlated with embeddedness) showed that only 3% of the variation in bed stability was due to HDI. This may lead to some loss of predictive power in the Glacier Macroinvertebrate MMI, but given the strong influence of substrate on macroinvertebrates, we felt this was an acceptable tradeoff.

The final Glacier Macroinvertebrate MMI (Table 24 and Table 25) was selected from three statistically equivalent candidate models (i.e., each had similar correlation with human disturbance and were indistinguishable based on their AIC scores) using a comparison of the interpretability of their component metrics and a series of validation steps. Importantly, our approach to estimating an MMI focuses on the overall statistical quality of the final model. This is discussed fully in Schoolmaster, Grace, and Schweiger (2012), Schoolmaster, Grace, et al. (2012), and Schoolmaster et al. (2013). Our objective in developing our MMI approach was to have the best possible (in a statistical sense) index to the ecological integrity of Glacier's streams based on the data employed. Our approach may sacrifice some ability to interpret component metrics. This may be especially so for macroinvertebrates, where some metrics are complex and/or have poorly understood ecological interpretation. Future work may focus on more structural interpretation of component metrics. Schweiger et al. (in preparation b) presents an example of such an effort using network data on wetlands in Rocky Mountain National Park.

Glacier National Park Macroinvertebrate Multimetric Index (MMI_{Gm}): Validation

Validation consisted of estimating each candidate Glacier Macroinvertebrate MMI with revisit and QAQC (Quality Assurance/Quality Control) sample events (not used in the model's initial construction or "calibration"). We then developed pairs of simple linear regression models between each candidate Glacier Macroinvertebrate MMI and HDI using calibration and validation data (separately) (Figure 58). These regression models did not include any additional covariates, as important environmental gradients are controlled for in the original estimation of the Glacier Macroinvertebrate MMI (Schoolmaster, Grace, and Schweiger 2012; Schoolmaster, Grace, et al. 2012; Schoolmaster et al. 2013). We next compared the calibration and validation version of each Glacier Macroinvertebrate MMI and evaluated patterns in the magnitude of change in adjusted r^2 and delta AIC. Finally, for each candidate Glacier Macroinvertebrate MMI, we also created a separate model in which calibration and validation data were used together (regressing Glacier Macroinvertebrate MMI on HDI across all possible events) and then tested for an effect of data source (calibration or validation).

Reductions in the adjusted r^2 and larger delta AICs from calibration to validation versions of each model were expected given how our modeling process optimized the statistical fit with calibration data. However we assume the model with the smallest reduction in adjusted r^2 and smallest change in AIC between calibration and validation was the version that most consistently estimated Glacier Macroinvertebrate MMI. Model variant 1 had the smallest changes (an adjusted r^2 = 0.74 for calibration to an adjusted r^2 = 0.34 for validation; AIC from 67.2 to 121.4; Figure 58). Model variant 1 also had component metrics that were more generally interpretable than the other two candidate models. Finally, for all three candidate Glacier Macroinvertebrate MMI models, the data source (calibration vs. validation) was insignificant. Had there been a significant effect of using calibration or validation data, it would have suggested that validation was less successful for a given model.

Glacier National Park Macroinvertebrate Multimetric Index (MMI_{Gm}): Interpretation

The relationship of the final Glacier Macroinvertebrate MMI with HDI was strong, with a negative correlation of -0.86 and an r^2 of 0.74 (Figure 59). The relationship of the final Glacier Macroinvertebrate MMI and HDI was markedly stronger than with any of its individual component metrics (Table 25), confirming the statistical and ecological advantage and

Table 25. Final component metrics of the Glacier National Park macroinvertebrate Multimetric Index (MMI_{Gm}). Table includes correlation (r) for each metric with HDI before and after scaling/adjustment by the coefficients and intercept as shown for each covariate in the model. Positive correlations with human disturbance (HDI) are shown in green and negative correlations are shown in red.

Metric Name	r (raw)	r (adjusted, scaled)	Intercept	HDI	Max stream temp	Catchment area	Lake effect	Embedded-ness	Total phosphorous	Runoff
Filterer (%)	0.24[1]	0.55[1]	0.01	0.09	0.00	0.00	0.21	0.00	0.00	0.00
Sediment sensitive richness	-0.29[2]	-0.51[2]	2.68	-1.55	0.00	0.00	0.00	0.00	0.00	-1.20
Predator (count)	-0.26[2]	-0.35[2]	136.51	-40.18	0.00	0.00	-49.16	0.00	0.00	0.00
Sediment sensitive (%)	0.19[1]	0.20[1]	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.00
Air breather richness	0.08[1]	0.17[1]	2.01	0.70	0.00	0.00	2.03	0.00	0.00	0.00
Air breather (%)	-0.10[2]	-0.15[2]	0.08	0.01	0.00	0.00	-0.09	0.00	0.00	0.06
Predator (%)	0.05[1]	0.01[1]	0.01	-0.01	0.00	0.00	0.00	0.00	0.00	0.00

[1] Positive correlation with human disturbance (HDI).

[2] Negative correlation with human disturbance (HDI).

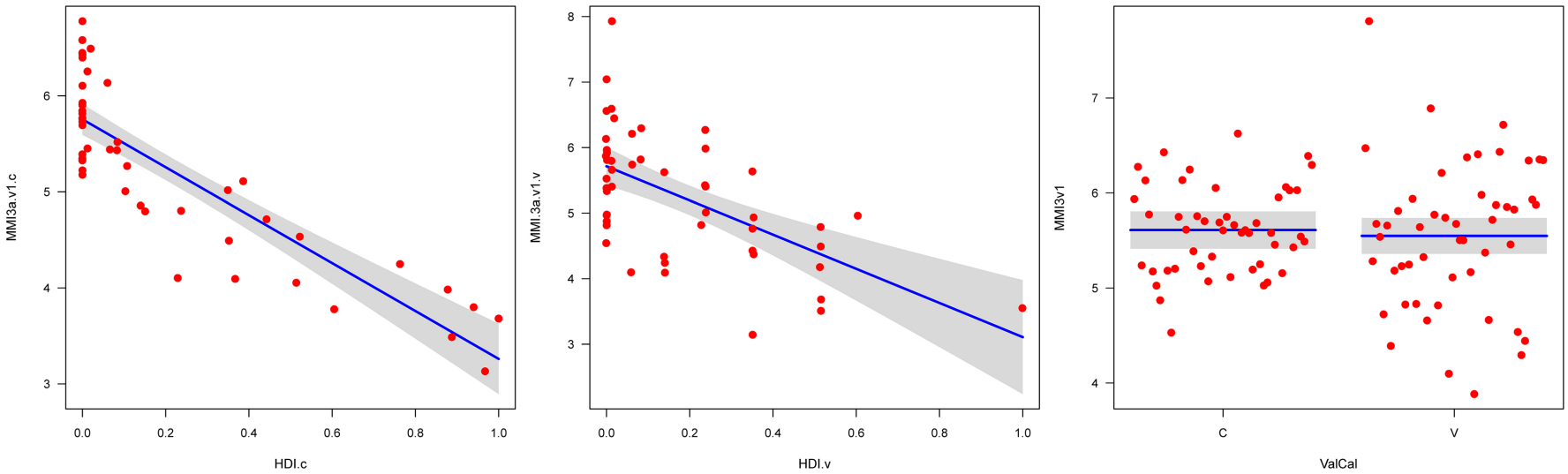


Figure 58. Calibration (MMI3a.v1.c) and validation (MMI3a.v1.v) bivariate models for the Glacier Macroinvertebrate Multimetric Index (MMI_{Gm}). Models are developed from assumed independent datasets. Linear fits and their 95% confidence intervals are shown with the blue line and gray shaded regions. The third panel shows calibration and validation data as points with their mean (horizontal blue lines) and 95% confidence intervals (gray shaded boxes).

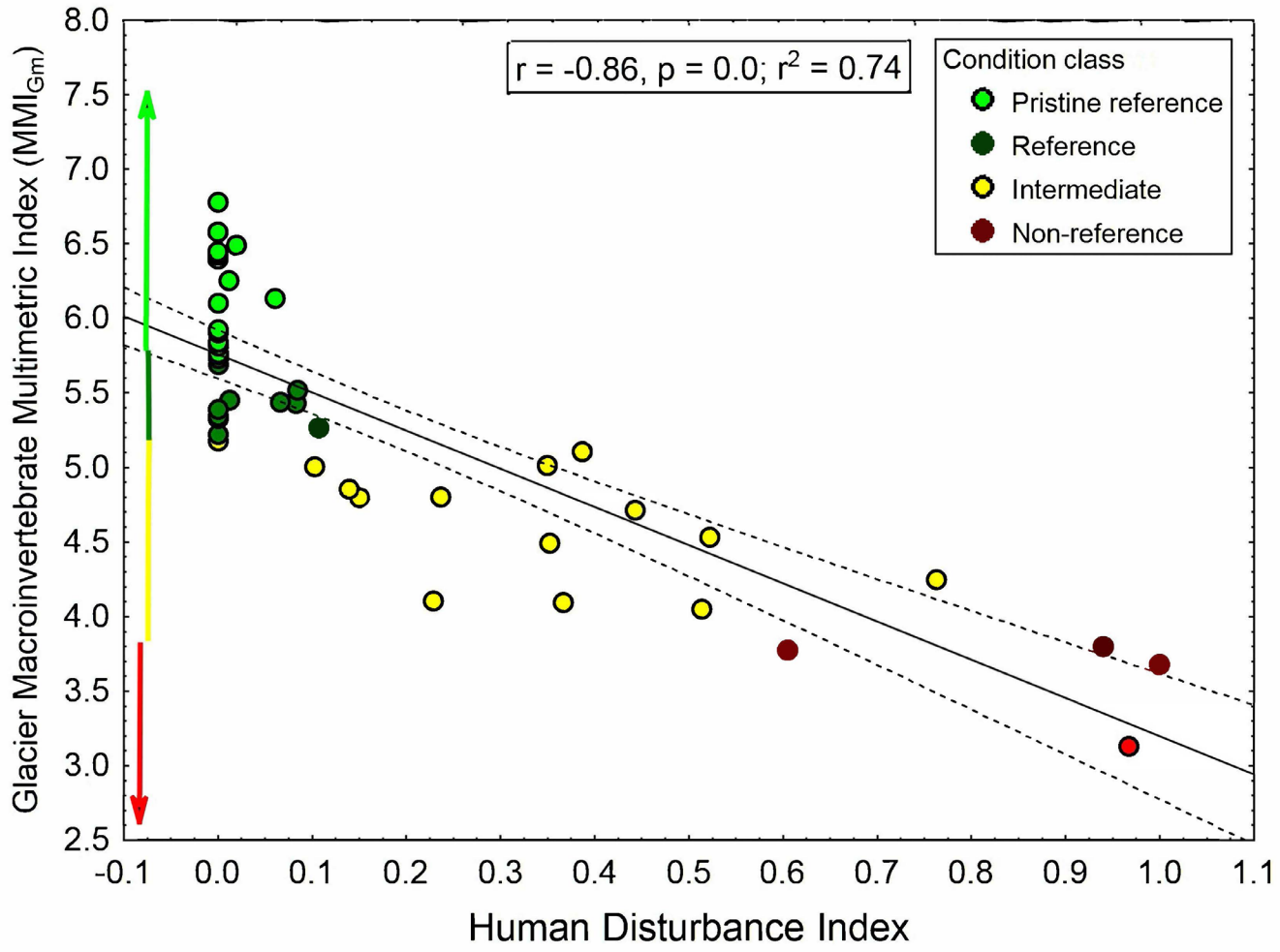


Figure 59. Bivariate relationship between the Glacier Macroinvertebrate Multimetric Index and the Human Disturbance Index (HDI), Glacier National Park, 2007–2009. Linear fit and its 95% confidence intervals area indicated by black solid and dashed lines, respectively. Point symbology and vertical lines along Y axis are derived from condition classes in MMI_{Gm}. Break points are predicted from disturbance values in HDI at 0 (negligible disturbance, light green), 0.23 (minor disturbance from the 75th percentile of HDI, dark green), and 0.76 (major disturbance from the 95th percentile of HDI, red). Moderate disturbance or intermediate condition (yellow) falls between minor and major assessment points.

parsimony of an MMI. Most component metrics had at least one meaningful relationship with a covariate and adjustment improved the signal in nearly all cases, confirming that controlling for these environmental gradients improved the model. Note that while three gradients (maximum water temperature, watershed area, and total phosphorous) did not have a relationship with a component metric, these gradients were related to many of the other metrics considered in the MMI modeling process and thus have a multivariate effect on the metrics included in the Glacier Macroinvertebrate MMI (Schoolmaster, Grace, and Schweiger 2012; Schoolmaster, Grace, et al. 2012; Schoolmaster et al. 2013).

The final Glacier Macroinvertebrate MMI (Table 25) includes seven component metrics within four classes: filterers (taxa that remove food particles from the water column usually with a net like device), sediment sensitive taxa (taxa that cannot persist in systems with high levels of fine sediments), predators (taxa at the top of the macroinvertebrate food chain), and air breathers (taxa that are adapted to low oxygen waters via structures that allow direct respiration with air). When combined in the MMI_{Gm}, these metrics are integrative of the suite of underlying ecological processes and/or response to human disturbance in the streams of Glacier. Interpreting component metrics can support insight into relationships between macroinvertebrate integrity and human disturbance. However, Glacier Macroinvertebrate MMI is ultimately intended as a stand-alone predictive tool – it has statistical and ecological properties as a whole that exceed its parts.

The proportion of each site's sample that was composed of filterers had the highest bivariate correlation with HDI. This functional feeding group often appears in MMIs (i.e., Kerans and Karr 1994). Suspended food particles removed by filterers often increase in systems with higher levels of human disturbance (Whiles and Dodds 2002; Wang and Kanehl 2003). Our model controlled for the tendency of filterers to also be strongly driven by proximity to lakes, where suspended food particles are more typical naturally. Sediment sensitive taxa richness was strongly negatively related to HDI. However, as sensitive taxa are replaced, the relative abundance of remaining sensitive taxa increases. This suggests some variance within the set of taxa classed as sensitive to sediment. In general this metric is also a common component metric in MMI models (i.e., Fore et al. 1996). We see suggestions of increased fine sediments in Glacier streams with more human disturbance (see our model of relative bed stability) but the response is complex (see the pattern between our stressor specific index of fine sediments and HDI). There were not strong patterns with environmental gradients and sediment sensitive taxa in MMI_{Gm}, although we do control for a negative relationship between sediment sensitive taxa and runoff. The absolute abundance of macroinvertebrates at the top of the food chain (predators) decreased with HDI. This is a well understood pattern in stream ecosystems. More ecologically intact streams tend to have more complete food webs, supporting large predators, such as many *Plecoptera* (stonefly) species (Vannote et al. 1980). Predator individuals decrease with increasing stress, perhaps also due to shifts in food resources and an increase in collectors and filterers. This metric is also seen in many other MMIs, including several from Montana DEQ (i.e., Jessup et al. 2006). Finally, the richness of taxa that are adapted for directly respiring in air increased with HDI. Our *in situ* water chemistry data suggested that around 14% of the park's waters had late summer midday dissolved oxygen levels below that needed to support sensitive juvenile salmonid species (see Table 12). The inclusion of this metric in MMI_{Gm} may reflect a similar response in the macroinvertebrate community.

Glacier National Park Macroinvertebrate Multimetric Index (MMI_{Gm}): Spatial pattern

The spatial pattern of the Glacier Macroinvertebrate MMI (Figure 60) resembles many of the other distributions for disturbance and chemistry or physical habitat presented in this report. This is important as it supports a structural relationship between these drivers and ecological response. In general, lower integrity occurs on the boundaries of the park and along visitor services corridors. In particular, these areas are the Railroad Creek tributary site, the trio of tributaries to the North Fork of the Flathead (Big Creek, Coal Creek, and Canyon Creek; Figure 61), and Divide Creek on the park's east border. These sites have historical and ongoing Clean Water Act 303d listings by Montana DEQ (2016) for various human caused disturbances in the US Forest Service land to the park's west, and in general, are in portions of the landscape with more of a human footprint. Notably MMI_{Gm} was more responsive to these disturbances at many of these sites than the state scale RIVPACS model (see next subsection below). Many backcountry wilderness streams had reference or pristine reference caliber macroinvertebrate ecological integrity. An interesting pattern was that sites on larger rivers, such as the North and Middle Forks of the Flathead, had intermediate condition. As discussed further in the next section, these calls are based on comparison to ecoregional assessment points and are best considered as baselines for future comparison. However this pattern is consistent across larger river sites and was also seen in the calibration data for these sites. This suggests either these sites either have reduced integrity macroinvertebrate communities or that the model is misclassifying these types of streams. It is common for bioassessment models generated largely from smaller streams to have issues with larger rivers, but more data are required to fully resolve this pattern.

Glacier National Park Macroinvertebrate Multimetric Index (MMI_{Gm}): Inference

Design-based summaries infer Glacier Macroinvertebrate MMI results to all sampleable Glacier streams in 2007–2009 (see Figure 62, Table 24). We use assessment points derived from models of the response in MMI_{Gm} at threshold values in HDI to interpret these results (note that these are also used in the site specific interpretations above). The median Glacier Macroinvertebrate MMI for the population of streams in Glacier was 5.46. Roughly 10% (with a 95% confidence interval of 0-22%) of the streams in the park were in a non-reference condition (as predicted from a major disturbance score of 0.76), with Glacier Macroinvertebrate MMI scores under 3.86. Around 20% percent was in a reference state, and around 48% (35–71%) was above a Glacier Macroinvertebrate MMI score of 5.76 and in a pristine reference condition (corresponding to a HDI score of 0). The ability to further classify reference streams into this "best of the best" state is unique to Glacier Macroinvertebrate MMI and one of the strengths of the model. The remainder (around 23%) was in an intermediate condition. These values are generally similar to many other metrics of condition, with a relatively small percentage of the park's streams in non-reference condition. As with all ecoregional assessment point based classifications, these are relative and should be used with

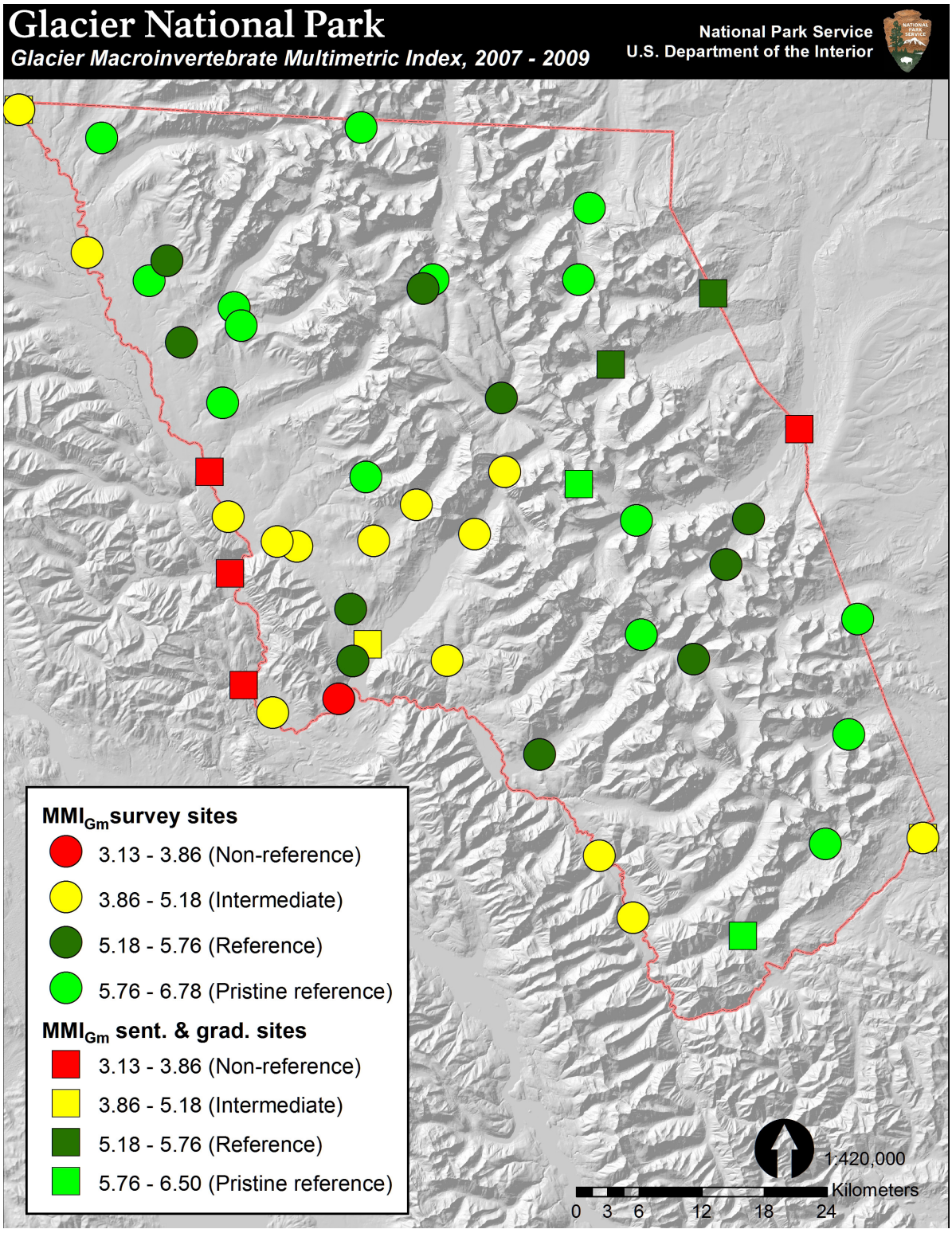


Figure 60. Map of the Glacier Macroinvertebrate Multimetric Index (MMI_{Gm}) at Stream Ecological Integrity survey, sentinel (sent.), and gradient (grad.) sites in Glacier National Park, 2007–2009. The four colored condition classes are based on ecoregional assessment points predicted from a model of Glacier Macroinvertebrate MMI and HDI (Human Disturbance Index) using the >95th percentile for major disturbance (red dots) and a <75th percentile for minor disturbance (dark green dots). A moderate disturbance class falls in between these values (yellow dots). For the negligible disturbance class we use the predicted Glacier Macroinvertebrate MMI value at HDI = 0 (light green dots). See Appendix A for a complete list of site numbers and names.

caution. This is especially so for our custom MMI models as the ecoregional reference site population is restricted to SEI sites alone. However, we have stronger confidence in Glacier Macroinvertebrate MMI scores in the pristine reference class, as these correspond to streams with no measurable human disturbance – a condition which we consider ecologically meaningful and we believe corresponds to the desired condition of Glacier streams in the wilderness and rustic management zones of the park (NPS 1999).

Existing large scale macroinvertebrate RIVPACS models applied to Glacier National Park

The quality of macroinvertebrate bioassessment models and metrics has been rapidly increasing over the last two decades nationwide, and in particular, in Montana through work by Montana DEQ and its partners. We estimated several existing larger scale macroinvertebrate bioassessment metrics using 2007–2009 Glacier SEI data. We based our choice of



Figure 61. Field crew collecting data on Big Creek in 2007, just outside the western border of Glacier National Park. The sample reach extended into a large culvert under the North Fork Road. (FLATHEAD LAKE BIOLOGICAL STATION/P. MATSON)

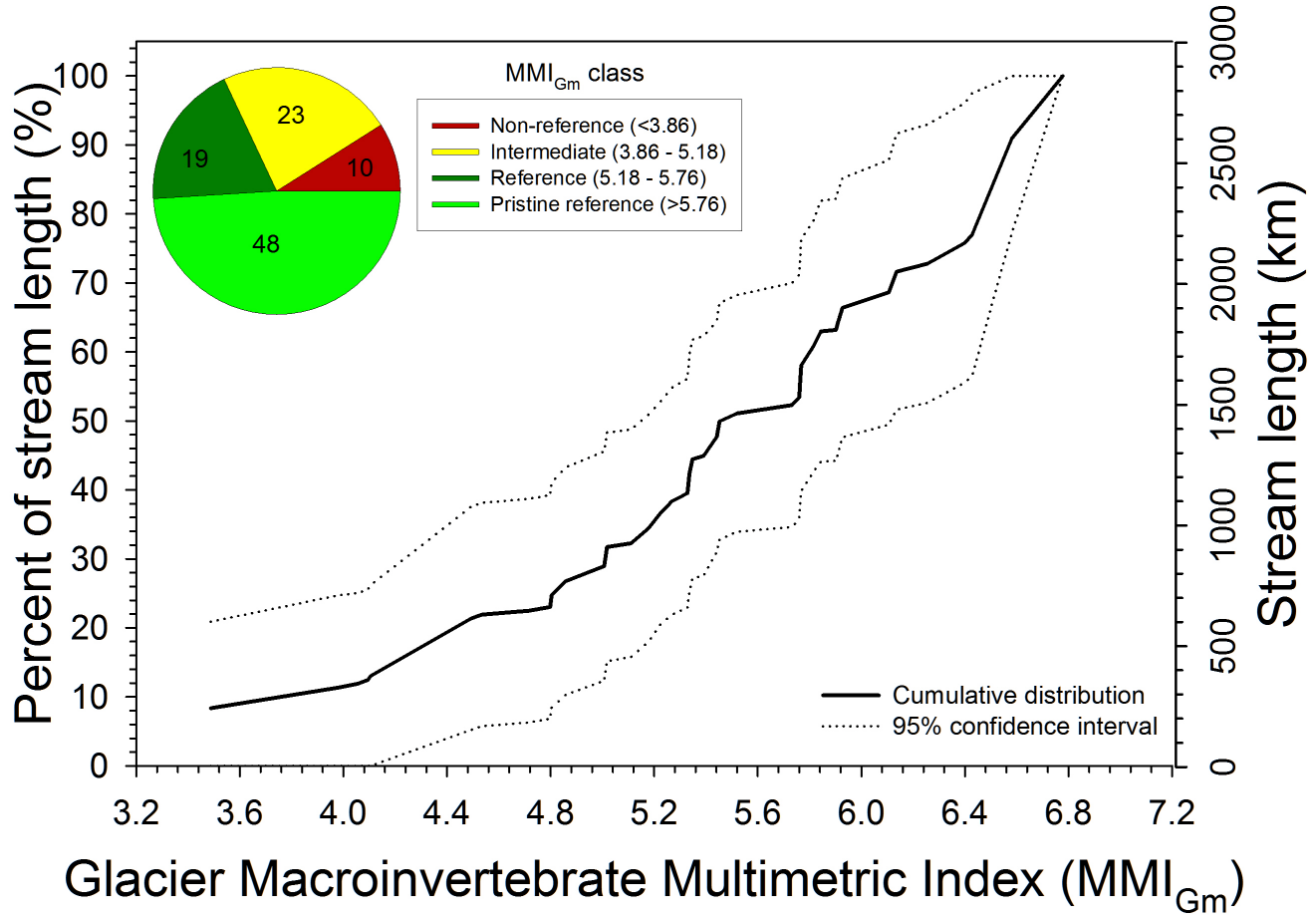


Figure 62. Cumulative distribution of the Glacier Macroinvertebrate Multimetric Index (MMI$_{Gm}$) in the population of Glacier National Park streams, 2007–2009. The left y-axis gives the percent of streams in the park and the right y-axis shows the actual estimated length of stream. A 95% confidence interval (dotted lines) around the percent values (heavy line) is also shown. Pie chart shows the percentage of the total length in pristine reference (light green), reference (dark green), intermediate (yellow), and non-reference (red) condition classes based on predicted assessment points from a model of MMI$_{Gm}$ and HDI (Human Disturbance Index). Pie charts do not include a confidence interval for each estimate in these classes, so they should be used with caution.

models to apply in part on Jessup et al. (2006) and Montana DEQ (2012a). In 2011 Montana DEQ dropped use of an MMI calibrated for large bioregions in the state and an older RIVPACS (River Invertebrate Prediction and Classification) model (Jessup et al. 2006) and focused instead on a new RIVPACS model and the Hilsenhoff Nutrient Index (Montana DEQ 2012a; Feldman and Jessup 2012). The older Montana DEQ MMI model was useful in previous drafts of this report and in other network parks (Schweiger et al. 2014a, b). However our Glacier Macroinvertebrate MMI, better calibrated to Glacier's streams, obviates the need for a larger scale, coarser MMI. The 2011 RIVPACS model has some statistical improvements over the older one; however, the sites used to calibrate it do not overlap with SEI sites in the park and test analyses and consultation with Montana DEQ suggested it performed poorly with SEI data (D. Feldman, pers. comm., 2012). However, RIVPACS models provide an interesting and useful complement to an MMI. Therefore, we use the older 2005 RIVPACS model (to complement the Glacier Macroinvertebrate MMI). Glacier SEI sites fall within the 2005 RIVPACS model's calibration site range and the model fits SEI data well. Should Montana DEQ ever need to assess stream(s) in Glacier using RIVPACS or MMI metrics, the network will work with them given these complexities.

RIVPACS models predict the taxonomic composition that should occur at a site given natural (i.e., reference) environmental characteristics (Hawkins 2005; Van Sickle 2008). In Montana's mountainous ecoregions these predictors include latitude, longitude, mean maximum annual air temperature, presence of a site in the Columbia River Basin, and watershed area. Natural variation in the multivariate space created by these variables is mirrored by natural variation in the taxonomic composition of the macroinvertebrate community. Deviation from this expected or natural taxonomic composition is caused by anthropogenic stressors, and the degree of this deviation is a direct measure of ecological integrity. Operationally this is estimated as the proportion of the taxa that should occur (or the expected; "E") in a sample under a reference state that were actually sampled (the observed; "O"). Values of O:E theoretically range from zero to around one, with values near one indicating reference condition and values approaching zero implying a non-reference state. Across the sites used to develop the model, the Montana DEQ 2005 RIVPACS model accounted for 76% of the variation in O, with a standard deviation of 0.18 in O:E – both indicating that the model was accurate and precise at the state scale.

O:E can be insensitive to stress-induced shifts in taxonomic composition that have little net effect on the number of reference-site taxa (Hawkins et al. 2000; Davies and Jackson 2006). The Bray Curtis (BC) dissimilarity statistic better accounts for which taxa occur at sites. Montana DEQ suggests using BC to determine if expected reference taxa are being replaced by more tolerant taxa indicative of a non-reference state. The BC index is most useful whenever a high (i.e., good) O:E score results from a sample collected from a known stressed stream. BC may better respond to macroinvertebrate communities that are in the process of adjusting to instream changes in stressor levels. BC is bounded between 0 and 1, where 0 means the two sites have the same composition or they share all taxa, and 1 means the two sites do not share any species (note this pattern is opposite from O:E).

From 2007 to 2009 the median O:E and BC for the population of streams in Glacier was 1.0 and 0.5, respectively. When compared to ecoregional assessment points, this indicated that just above 70% of the stream in the park was in a reference state (Table 24, Figure 63). This suggests that the observed macroinvertebrate taxonomic composition was not meaningfully different from an expected reference composition or species list in this portion of the park's streams (relative to the best ecoregion reference sites). The connection between human disturbance and ecological integrity in the larger scale RIVPACS model is not as direct as with MMI_{Gm} (see above). Nevertheless, following our assessment strategy, we characterize this result as an indicator of a synthetic ecological response in stream condition (vs. disturbance), with the assumption that this also corresponds to minor human disturbance levels. Both metrics also suggested that 5 to 10% of the park's streams were in a non-reference state (with assumedly major disturbance levels). The balance of about 17–24% of the stream in the park was in intermediate condition. Because the RIVPACs model was not calibrated to Glacier (e.g., it was created by Montana DEQ for bioregions in the state), we are not able to infer the percentage of the streams in the park that are a pristine ecological condition corresponding to negligible or zero measurable human disturbance. A Montana DEQ criterion of 0.8 is available for the 2005 O:E model (Montana DEQ 2012a) based on a probability of capture of at least 0.5. As noted above, the version of the model that includes all taxa (i.e., rare taxa with a probability of capture approaching 0) is the better application in Glacier. However, if we assumed that the DEQ criterion is applicable, about 84% of the park's streams are above this Montana DEQ "impaired" or "does not meet designated uses" criteria (what we would call a non-reference condi-

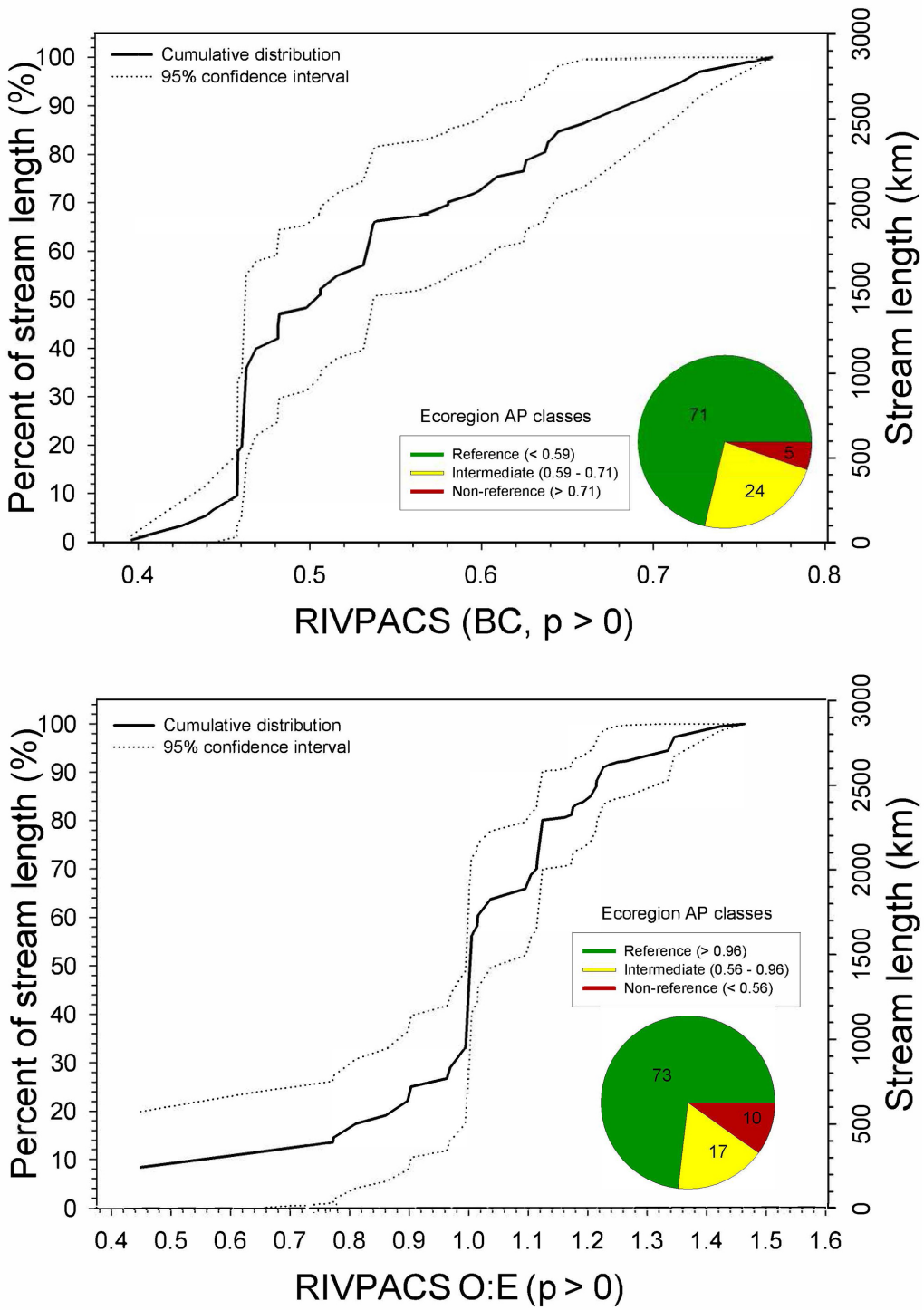


Figure 63. Cumulative distributions of River Invertebrate Prediction and Classification System (RIVPACS) model results for the population of Glacier National Park streams, 2007–2009. The RIVPACS model was created by the Montana Department of Environmental Quality. The top graph shows the Bray Curtis dissimilarity statistic (BC) and the bottom graph shows a ratio of observed to expected values (O:E), both at a p (probability of capture) > 0. The left y-axis gives the percent of streams in the park and the right y-axis shows the actual estimated length of stream. A 95% confidence interval (dotted lines) around the percent values (heavy line) is also shown. Pie chart shows the percentage of the total length in reference (dark green), intermediate (yellow), and non-reference (red) classes based on comparisons with ecoregional assessment points (AP). Pie charts do not include a confidence interval for each estimate in these classes, so they should be used with caution.

tion). This is in line with the results we see in the comparisons to ecoregional assessment points.

Figure 64 shows the spatial distribution of O:E and BC values across the park. In general, lower integrity occurs on the boundaries of the park and along visitor services corridors (i.e., the Going to the Sun Road that bisects the park east to west). This spatial pattern is clearer with the BC metric. As presented in several places in this report, sites on tributaries to Railroad and Rubideau Creeks with high HDI scores and/or levels of physical habitat variables, such as fine sediments, that differed from values expected under natural condition had reduced ecological integrity. Most backcountry wilderness streams had reference caliber macroinvertebrate community composition, although sites with higher but natural nutrient concentrations, such as our site on a tributary to Bowman Lake, had slightly reduced integrity. Given a lack of human disturbance at these more remote stream sites, we expect these are misclassified due to error in the application of the state scale RIVPACS model to Glacier. More data are needed to fully resolve this.

Existing large scale macroinvertebrate RIVPACS models: Exploratory model applied to Glacier National Park

Next, we present exploratory models of the patterns within RIVPACS bioassessment metrics. Models were developed for four metrics derived from the 2005 Montana DEQ RIVPACS model (O:E and BC at $p > 0$ and $p > 0.5$). However, we only present results for O:E at $p > 0$ here as this model was the only one that included HDI (or any type of human disturbance independent variable) in its final formulation. Models for the other three metrics were robust and included interesting independent variables. Yet all were natural environmental gradients. This is, by itself, revealing of the overriding importance of natural patterns in macroinvertebrate community composition in Glacier.

We selected potential independent variables based on our collective ecological experience, statistical attributes, and those that might also have the most utility for stream resource management in Glacier. For additional details on model construction, see the methods, Appendix D, and/or the introduction to this same subject within the human disturbance section above. Note that we don't model MMI_{Gm} results largely because the methods used to estimate this MMI account for natural gradients and multivariate relationships within the response of macroinvertebrates to disturbance at the scale of Glacier.

Our final model of O:E had seven independent variables (Table 26). It was highly significant ($p < 8.294e\text{-}06$), with an adjusted r^2 of 0.55, indicating a meaningful proportion of the variation in O:E was accounted for in the model. Complete model details are presented in Appendix F. We focus our interpretation here on select variables in the model that either had high relative importance, low p-values, and/or interesting relationships as drivers or covariates of O:E. We use conditional plots of partial residuals to visualize the model (Larsen and McCleary 1972; Breheny and Burchett 2013).

Just over 40% of the variation in Montana DEQ 2005 RIVPACS O:E, ($p > 0$) was due to stream order. Stream order encapsulates a suite of geophysical and biological differences across streams (Vannote et al. 1980) and is often included in models of patterning in macroinvertebrates or other stream biota (e.g., Crunkilton and Duchrow 1991; Waite et al. 2000). Within our 2007–2009 data, most sites with relatively lower O:E scores (in comparison to stream order 3; Figure 65) were stream order 2. It is not likely that there is anything structural about a stream order 2 causing lower O:E; however, clearly stream order structures a large portion of the variation in O:E and its inclusion in the model is important to facilitate interpretation of other variables. Catchment size was also important, accounting for 16% of the variation in O:E, with higher O:E ratios in streams with larger catchments (note that catchment area was log transformed, so the increase in O:E with increasing watershed size is marginal). Watershed area is probably mostly a covariate with other drivers that structure macroinvertebrate communities (similar to stream order). However, watershed size may constrain spatial arrangement of patches, translating to a direct impact on stream condition (Strayer et al. 2003; King et al. 2005). Therefore watershed size, especially at small scales where single patches can dominate a catchment, can be a structural predictor of macroinvertebrate communities. For example in Glacier, several of the smallest catchments in the park are at streams with relatively high levels of human disturbance where we also see a negative response in ecological integrity. We also see lower O:E with higher levels of suspended sediment (accounting for 15% of the variation in O:E) and higher O:E in streams with more narrow wetted widths (11%). Fine and suspended sediments are well documented as usually having negative effects on reference caliber macroinvertebrate communities (i.e., Angradi 1999), especially in systems like Glacier (Griffith et al. 2005; Relyea et al. 2000, 2012; Hartwig et al. 2016). The pattern with smaller wetted width streams having higher O:E follows from many bioassessments with smaller headwater systems often supporting regional

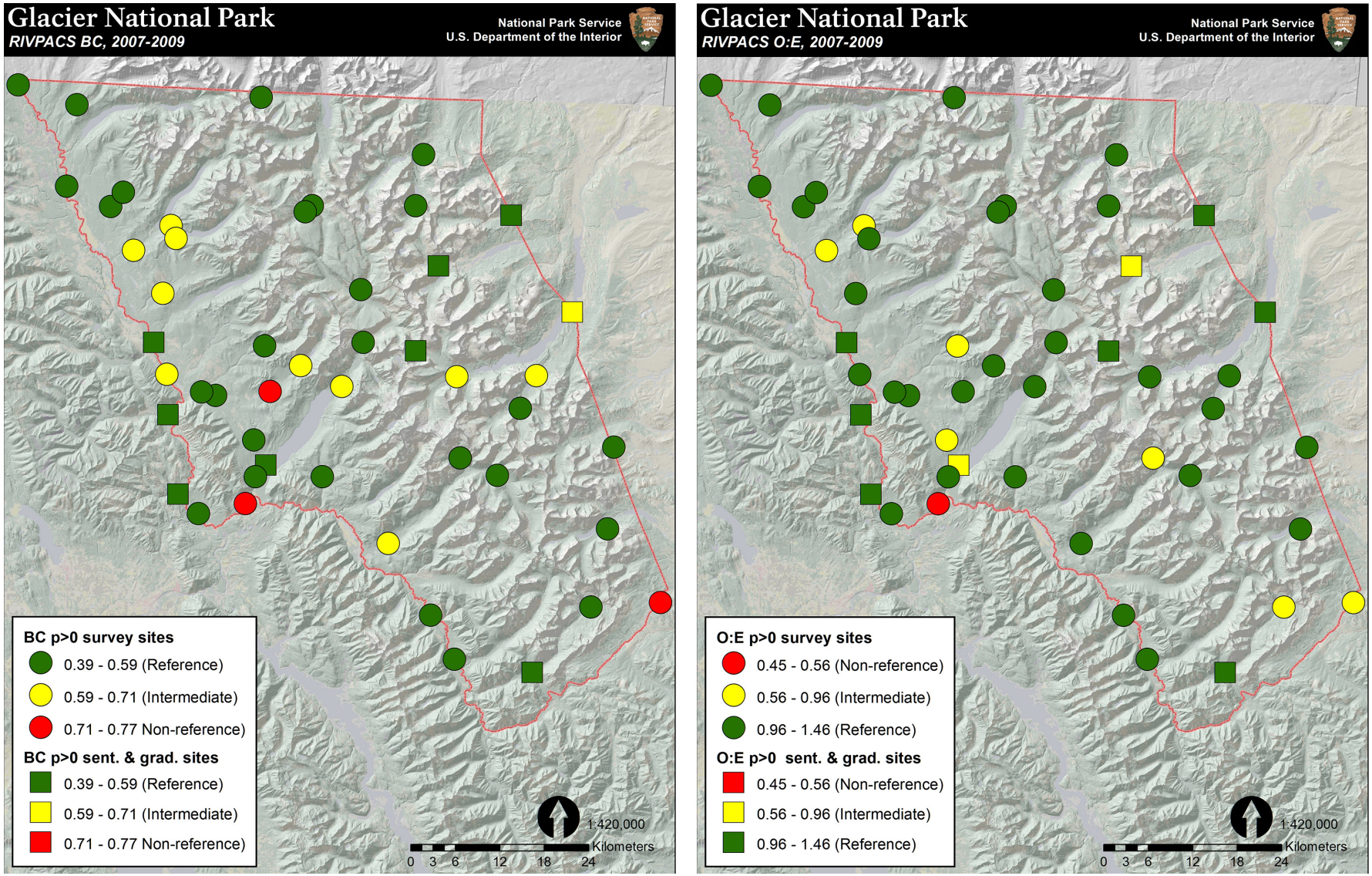


Figure 64. Map of River Invertebrate Prediction and Classification System (RIVPACS) model results at Stream Ecological Integrity survey, sentinel (sent.), and gradient (grad.) sites in Glacier National Park, 2007–2009. The RIVPACS model was developed by Montana Department of Environmental Quality. The left figure shows results for a Bray Curtis dissimilarity statistic (BC) and the right figure shows results from a ratio of observed to expected values (O:E), both at p (probability of capture) > 0. Colored condition classes are based on percentile assessment points derived from ecoregional reference stream sites in the park and its surrounding ecoregions. Red color indicates sites with observed macroinvertebrate taxonomic composition most dissimilar from expected composition under a reference condition. See Appendix A for a complete list of site numbers and names.

Table 26. Final exploratory model of observed to expected ratio using River Invertebrate Prediction and Classification System (RIVPACS) at p (probability of capture) > 0 in 2007–2009 at Glacier National Park. The 2005 RIVPACS model was developed by Montana Department of Environmental Quality. Independent variables in our model were selected using Akaike Information Criterion (AIC) and expert opinion from 22 candidates. Relative importance (Rel. Imp %) is the total amount of explained variance for each variable expressed as a percentage. Stream order is treated as a factor and all estimates are relative to stream order three (the most common type). *Relative importance value of stream order is for all groups combined. East vs. west is treated as a factor and all estimates are relative to sites on the east side of the park.

Model component	Estimate	SE	t	p	Rel. Imp. (%)
Intercept	-0.41	0.71	-0.58	0.57	–
Stream order—1	-0.11	0.11	-1.00	0.32	–
Stream order—2	-0.25	0.08	-3.22	0.00	–
Stream order—4	-0.04	0.06	-0.70	0.49	–
Stream order—5	0.13	0.10	1.31	0.20	–
Stream order—6	-0.04	0.16	-0.27	0.79	–
Stream order (vs. order 3)	–	–	–	–	0.40*
East vs. west	-0.09	0.05	-1.80	0.08	0.02
Catchment area (km^2, log)	0.10	0.04	2.47	0.02	0.16
Human Disturbance Index	-0.20	0.08	-2.58	0.01	0.07
Distance to closest lake (m, log)	0.04	0.02	2.49	0.02	0.07
Total suspended solids (mg/l, log)	-0.07	0.03	-2.38	0.02	0.15
Mean stream width (cm, log)	-0.14	0.06	-2.50	0.02	0.11

Notes: SE = standard error of coefficient, t = t test value, p = probability of the t. Residual standard error: 0.1275 on 37 degrees of freedom, Multiple R^2: 0.6554, Adjusted R^2: 0.553 F-statistic: 6.398 on 11 and 37 DF, p-value: 8.294e-06.

ecological integrity (i.e., Freeman et al. 2007), but in our model this pattern is somewhat inconsistent with catchment area, suggesting an interesting interaction between these two predictors. Alternatively, the patterns with large watershed sites having higher O:E may instead reflect a low number of larger rivers in the calibration data used for the Montana DEQ model. Finally, we see a fairly steep (coefficient of -0.2) and consistent decrease in O:E with increasing HDI, accounting for 7% of the variation in O:E. As noted, this is the only model of the four Montana DEQ RIVPACS metrics that included human disturbance. It is not clear why the model that included all taxa responded to HDI and the common taxa (p > 0.5) model did not, nor why we did not see this pattern in either BC metric. BC is often better at refining the interpretation of sites with high O:E despite being influenced by human disturbance – this situation does not really arise in the Glacier data (it does in another network park, Grant-Kohrs Ranch National Historic Site, Schweiger et al. 2011). This relationship was also not nearly as clear in a univariate model between O:E and HDI (where the r value was -0.12 with an r^2 0.01). In the current model with multiple independent variables, partial residuals, as in Figure 65, clearly show the importance (in terms of predicting power for O:E) of HDI with all other independent variables controlled for. This is the best evidence we have for the utility of the large scale RIVPACS metrics in assessing the streams of Glacier.

Existing large scale macroinvertebrate RIVPACS models applied to Glacier National Park: Caveats

The general concordance in results across MMI_{Gm} and the Montana DEQ RIVPACS metrics provides good weight of evidence that the 2005 RIVPACS model (especially the O:E index with p > 0), while not truly calibrated to Glacier, is responding to relationships between the park's macroinvertebrate communities, as an indicator of stream integrity, and human disturbance. This gives us confidence that assessments done by the state or other partners using these or similar tools will likely correctly approximate stream condition in the park. However there are issues with applying models like these to Glacier (Cao and Hawkins 2011) as discussed below.

The Montana DEQ RIVPACS models are useful tools for assessing stream ecological integrity at the state scale where the fit between O and E is good, there is little variance in O:E across sites groupings based on macroinvertebrate community composition (the ideal), and the model separates classes of human disturbance well (Jessup et al. 2006; Montana DEQ 2012a). Our application of these broad scale tools to SEI

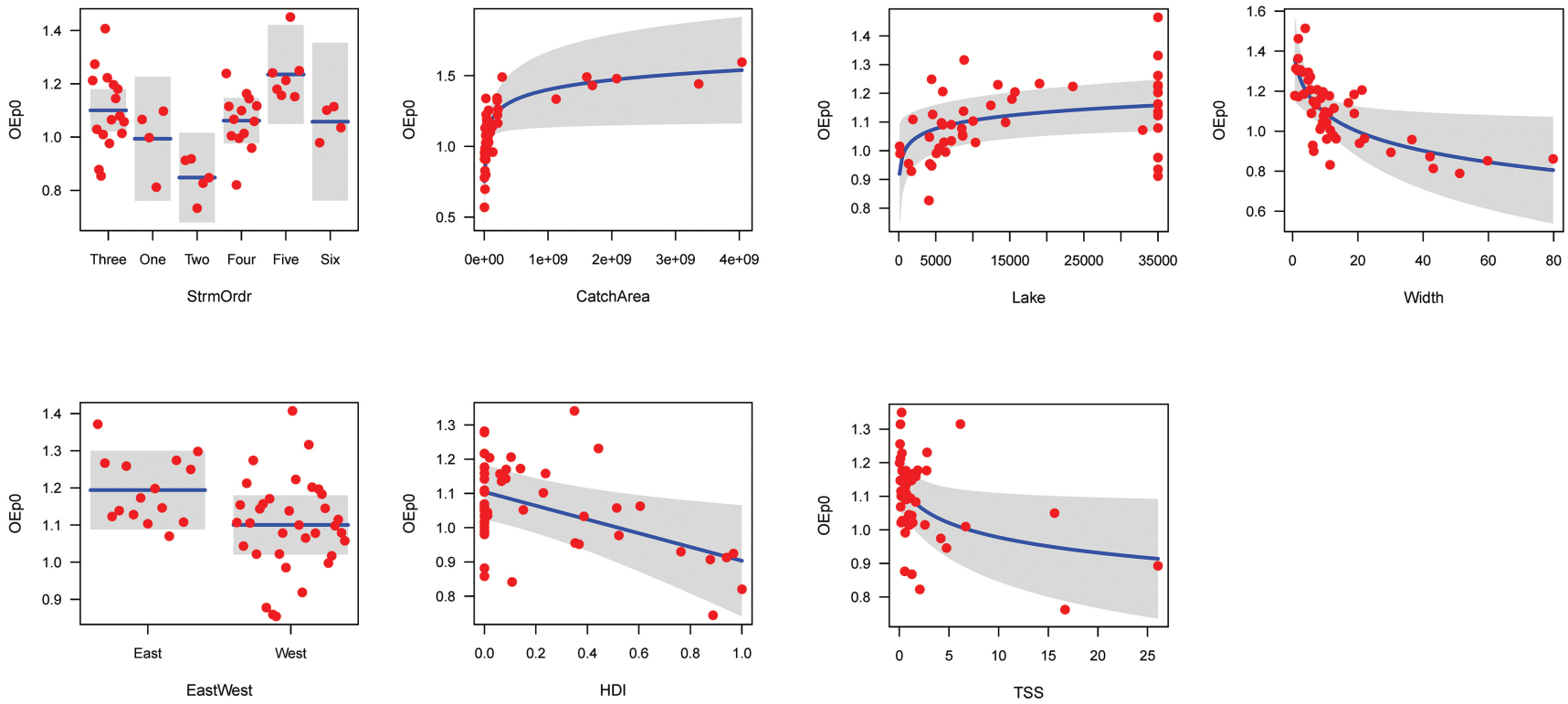


Figure 65. Partial residual plots of predictors of the 2005 River Invertebrate Prediction and Classification System (RIVPACS) model using the observed to expected ratio (OEp0, or O:E) for all macroinvertebrate taxa in Glacier National Park, 2007–2009. The RIVPACS model was developed by Montana Department of Environmental Quality. Conditional partial residuals show the relationship between each unique predictor and O:E, with all other variables held constant at the median for numeric variables and most common level for factors. All variables are shown back transformed to their original scale as applicable. Plots of numeric predictors include a best fit line and 95% confidence bands around this fit. Box plots of factorial variables include the reference category first or on the leftmost side of the figure and the 95% confidence interval as the bounding box around the variable's median. Codes in figures are: OEp0 = Montana DEQ 2005 RIVPACS O:E using all taxa; StrmOrdr = Strahler stream order; CatchArea = area of site's catchment (km^2); Lake = stream distance to closest lake outlet (m); Width = mean wetted width (m); EastWest = east or west side of the continental divide; HDI = Human Disturbance Index; TSS = total suspended sediment (mg/l). See the full model results in Appendix F and Table 26.

data is consistent with monitoring and assessment of stream resources by NPS and its partners – we do the same with water chemistry criteria, etc. The existing DEQ models are created across a broad spectrum of calibration sites. While the models attempt to partition the natural variation into bioregions (i.e. mountain type streams vs. lower elevation plains streams) they invariably encompasses broader and different disturbance gradients than that present in Glacier. This can cause a misfit between the models calibration and SEI sites. Ode et al. (2008) and Aroviita et al. (2009) show that calibration with more localized data better accounted for the effects of key natural environmental gradients on assemblage composition and, hence, the accuracy in predicting ecological integrity. This is the primary motivation behind our MMI_{Gm} model and motivation for future on a RIVPACS model scaled to the park.

The choice to include rare species or not in a bioassessment model is debated (Cao et al. 1998; Clarke and Murphy 2006; Van Sickle et al. 2007). Taxa which are more sensitive to stress and generally occur at reference sites are naturally less widespread and thus tend to have considerably lower average site-specific expected probabilities. Therefore, use of higher probability of capture thresholds (i.e., $p > 0.5$) can exclude more sensitive taxa and lead to a lack of sensitivity in the estimation of condition. If we rely on common taxa, we assume that human disturbance impacts only a small number of taxa and to the greatest extent (Cao and Williams 1999). Ford (1989) warned that the early loss of stressor-intolerant species may be missed if the initial abundance of sensitive species is low and spatial and temporal heterogeneity is high. Removing rare taxa does statistically improve the Montana DEQ RIVPACS models when applied across the state; however, if this was applied to a more discrete landscape it would shorten the list of taxa to be compared and likely lead to an underestimation of the difference between undisturbed and impacted sites. Thus we feel using all taxa ($p > 0$) is the correct solution for the scale of the park and produces more interpretable results.

A new RIVPACS model calibrated to the park or a broader region but including the stream types in the park would be useful. The 2011 DEQ model attempted to do this but lacked a complete range of calibration sites relevant to the park. We will work with the state if needed to advance this modeling as possible and on any application of their tools to streams in the park.

Existing stressor specific macroinvertebrate models applied to Glacier National Park

The overall condition of a stream as reflected in life or natural history based metrics or taxonomic composition as estimated by MMI_{Gm} and RIVPACS models is a fundamental aspect of ecological integrity. However, it is also useful to directly link macroinvertebrate response to important specific stressors in Glacier. This may generate assessments that are more diagnostic and potentially useful to resource management.

Construction of these types of metrics requires that each taxon be assigned a number indicating its level of sensitivity to a specific stressor. We use standard tolerance scores and thus must assume that there are not within species, localized variances in these responses. One way of overcoming this problem is to construct a suite of tolerance based indices across both macroinvertebrates (three models) and diatoms (four models), each assembled using sensitivity numbers targeted to a particular impact (Chang et al. 2014).

The Fine Sediment Biotic Index (FSBI) is a tolerance based metric that describes the response within a benthic community to fine sediment (Relyea et al. 2000). Increased fine sediment (beyond that which occurs naturally in a given system) can influence stream biota by reducing photosynthesis and thus production, physically abrading algae, or preventing attachment of autotrophs to substrate surfaces (Brookes 1986; Relyea et al. 2012). The FSBI ranges from 0 to 10, with lower scores indicating a community that includes more taxa likely to persist in systems with higher levels of fine sediments. Higher scores describe assemblages that are more intolerant of fine sediment (and that therefore occur where there is less sediment). The FSBI was developed for streams in the northwestern United States from 561 stream sites, several of which are in Glacier, and using many taxa that occur in Glacier. Relyea et al. (2012) developed four classes of fine sediment tolerance but did not classify these into condition classes. Therefore, we use ecoregional reference sites to develop assessment points. From 2007 to 2009, the median FSBI for the population of streams in Glacier was 4.8. When compared to ecoregional assessment points, this indicated that about 69% of the stream in the park was in a reference state with minor disturbance (Table 24). Around 12% was in a non-reference state (with assumedly major disturbance levels).

Given that the FSBI was developed to diagnose fine sediment, we restrict our modeling of these data to bivariate fits with measures of smaller sediments. The best relationship we found was with percent fines (Figure 66), in which a fairly strong negative relationship was seen. This suggests a biological response to fine sediments in the park streams. However we do not see strong statistical evidence of a connection between fine sediment and human disturbance across the

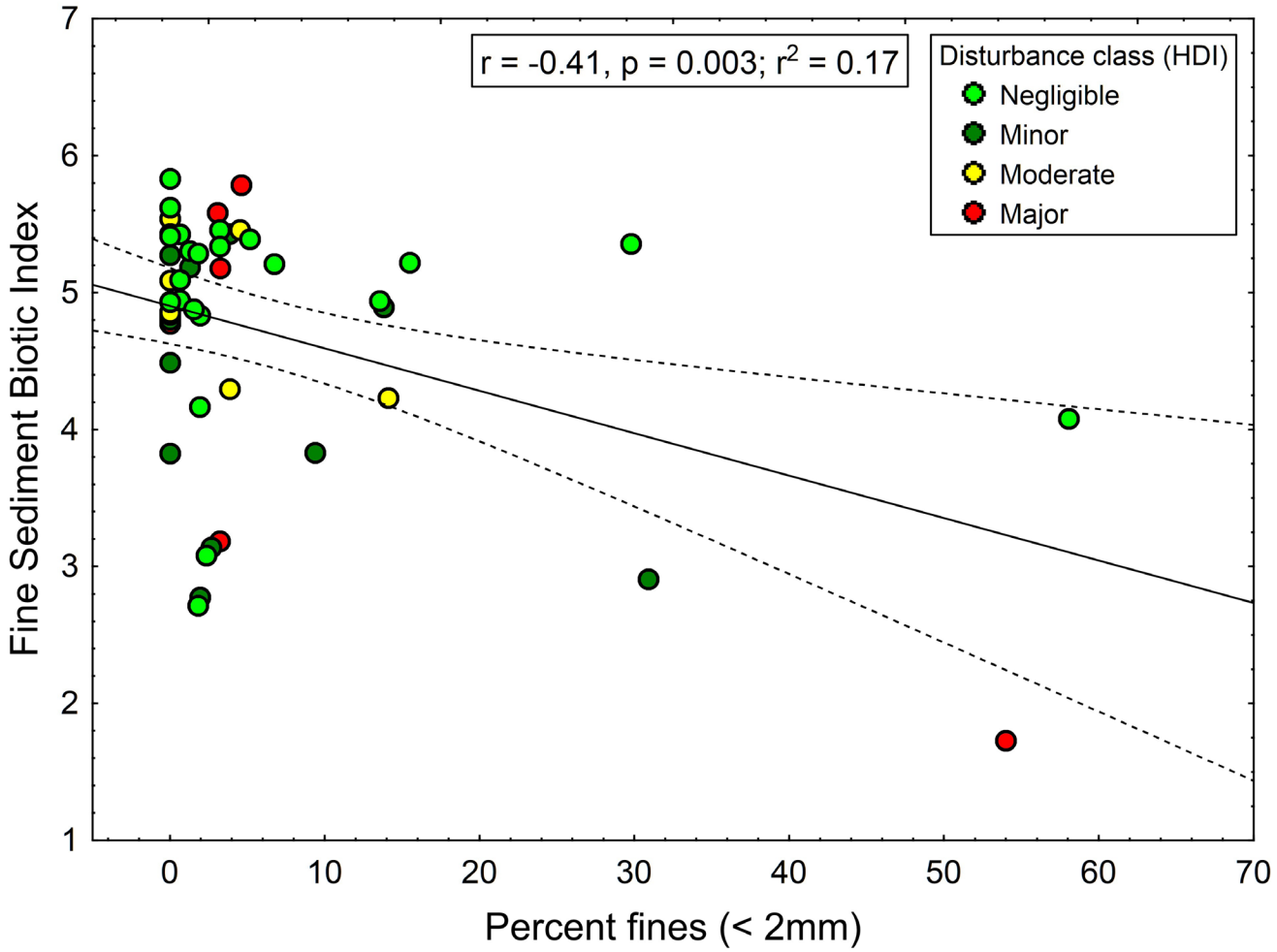


Figure 66. Linear bivariate model of Fine Sediment Biotic Index (FSBI) in Glacier National Park, 2007–2009. Points are classified by disturbance classes within the Human Disturbance Index, with red color indicating the highest level of human disturbance.

park's streams as a whole. Select streams (i.e., Rubideau Creek tributary below the park's water supply) do have high levels of fine sediments, elevated HDI, and lower FSBI scores (driven by many taxa tolerant of fines). Therefore, the index may have some utility in diagnosing biological response where we also have evidence of human disturbance, but this should be treated with caution.

Figure 67 shows the spatial pattern in FSBI scores across the park. Select sites in or near the park's front country with lower FSBI scores (more fine sediment tolerant taxa) indicate potential issues with disturbance. However, some sites in a moderate class are in the park's backcountry, suggesting natural sources for fine sediments in these streams.

The Temperature Preference Index (TPI; Brandt 2001) is derived from estimates of temperature optima for a suite of macroinvertebrate taxa. It provides a useful bioassay of temperature dynamics in a stream – in a sense the TPI treats the macroinvertebrate community as a natural temperature logger, integrating highly variable water temperatures experienced across the life cycles of taxa in a stream. As noted throughout this report, stream water temperature is a key piece of the ecology of the park's streams. Yet it is difficult to measure at all sites – the TPI may be an efficient way to accomplish this. TPI in Glacier in 2007–2009 ranged from about 10 to 18, with lower scores indicating a macroinvertebrate community more likely to persist in systems with lower water temperatures. We use ecoregional reference sites to develop assessment points for the TPI. In comparison to ecoregional assessment points, about 75% of the stream in the park was in a reference state, with only minor disturbance (Table 24). Around 3% was in a non-reference state (or had major disturbance levels). Most of the park's streams have macroinvertebrate communities adapted to colder

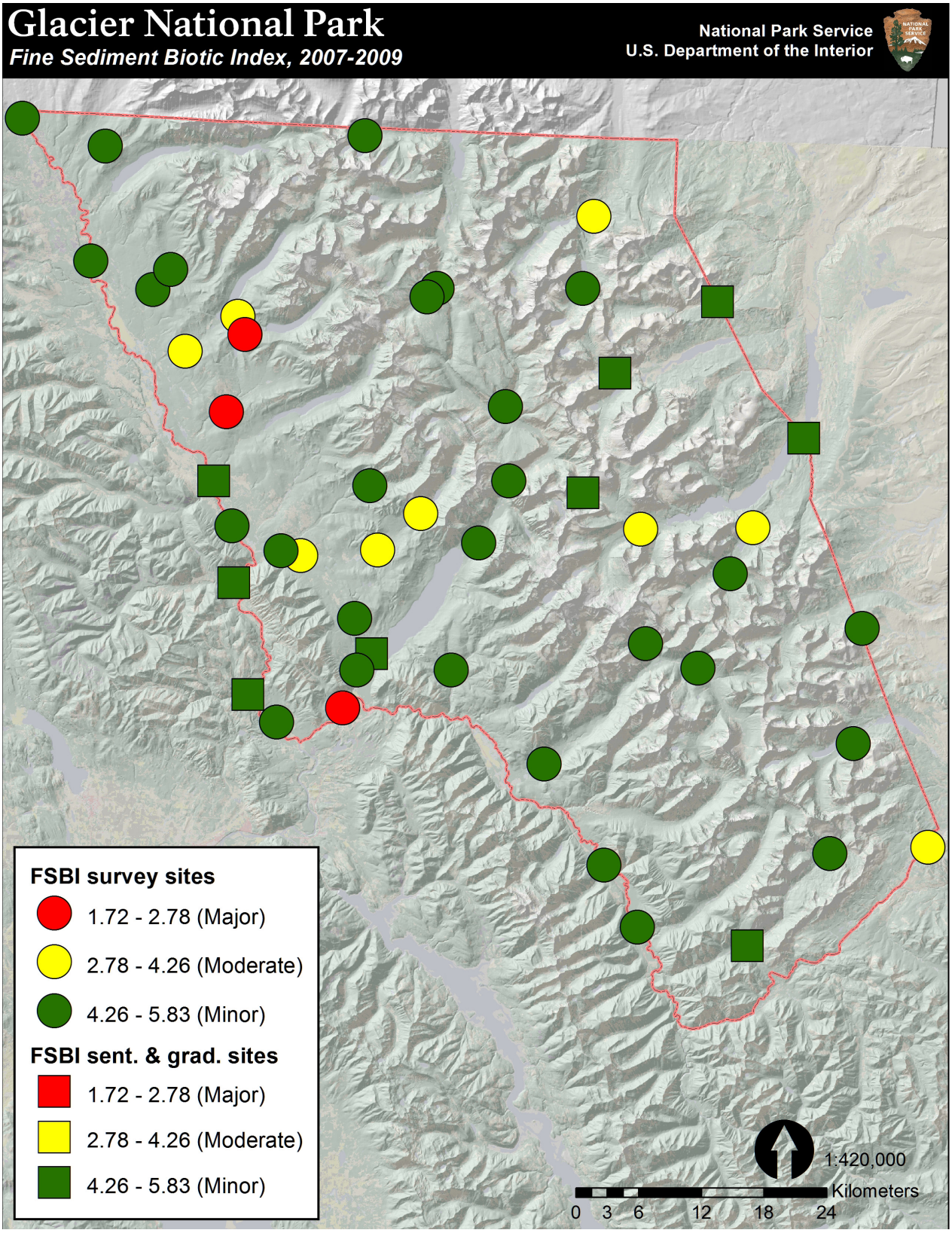


Figure 67. Map of Fine Sediment Biotic Index (FSBI) at Stream Ecological Integrity survey, sentinel (sent.), and gradient (grad.) sites in Glacier National Park, 2007–2009. Colored disturbance classes are based on percentile assessment points derived from ecoregional reference stream sites in the park and its surrounding ecoregions. Red color indicates sites with macroinvertebrate communities more tolerant of fine sediments. See Appendix A for a complete list of site numbers and names.

waters. This is especially the case for endemic alpine taxa like *Lednia tumana* and *Zapada glacier* (Muhlfeld et al. 2011; Giersch et al. 2016). The TPI is strongly correlated with both instantaneous midday late summer water temperature and the maximum temperature in each site's catchment based on mean annual 2008 air temperature (Isaak et al. 2016; Figure 68). This suggests it is a useful diagnostic metric and may be important as climate change continues to warm the park's streams, especially in alpine areas.

Hamilton et al. (2010), Stamp et al. (2010), and EPA (2008) suggest that synthetic models like MMIs and RIVPACS may be confounded by shifts in climate regimes over time given complex effects of climate change on both reference and non-reference sites (in comparison to other stressors that are largely absent from reference streams). Using an index like the TPI may help better understand these patterns. In Glacier there is a surprisingly strong relationship between higher ecological integrity sites and macroinvertebrate communities more tolerant of colder water (Figure 69). However there is not a strong bivariate relationship between TPI and HDI, suggesting there are likely important environmental gradients also affecting the relationship. Therefore, while TPI does not reveal a simple response in the macroinvertebrate community to HDI-driven shifts in stream water temperature, it may suggest that as climate continues to shift, bioassessment will need to react to climate driven changes as these temperature shifts affect both reference and non-reference streams.

Our final stressor specific metric is the Hilsenhoff Biotic Index (HBI; Hilsenhoff 1982), which estimates the tolerance of the macroinvertebrate community to nutrient concentration. Taxa are assigned a tolerance number from 0 to 10 pertaining to that group's known sensitivity to organic pollutants. A score of 0 is the most sensitive, while a score of 10 is the most tolerant. Montana DEQ and EPA recently carried out

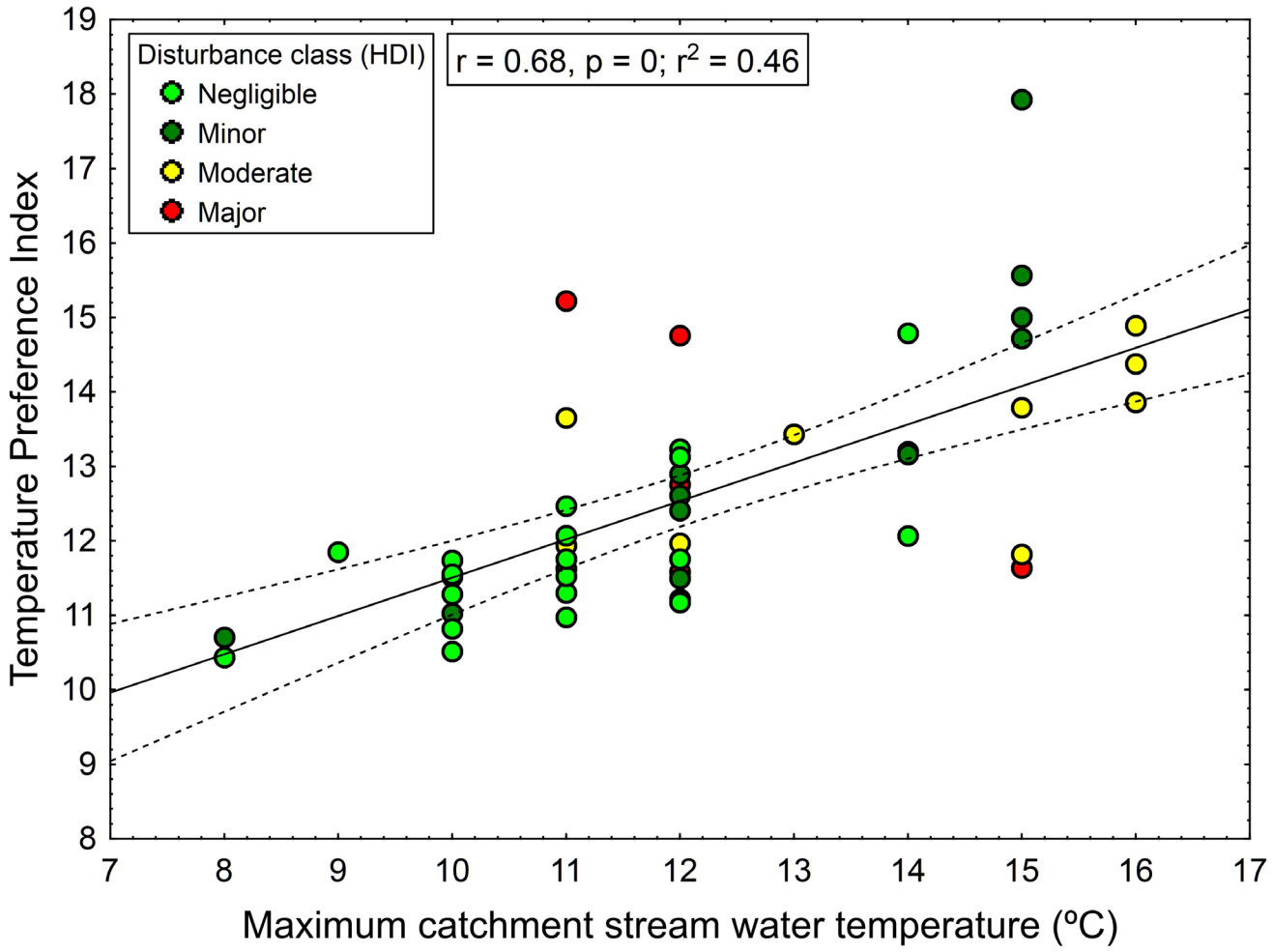


Figure 68. Linear bivariate model of the Temperature Preference Index (TPI) and the maximum catchment stream water temperature (ºC, Isaak et al. 2016) in Glacier National Park, 2007–2009. Points are classified by disturbance classes within the Human Disturbance Index, with red color indicating the highest level of human disturbance.

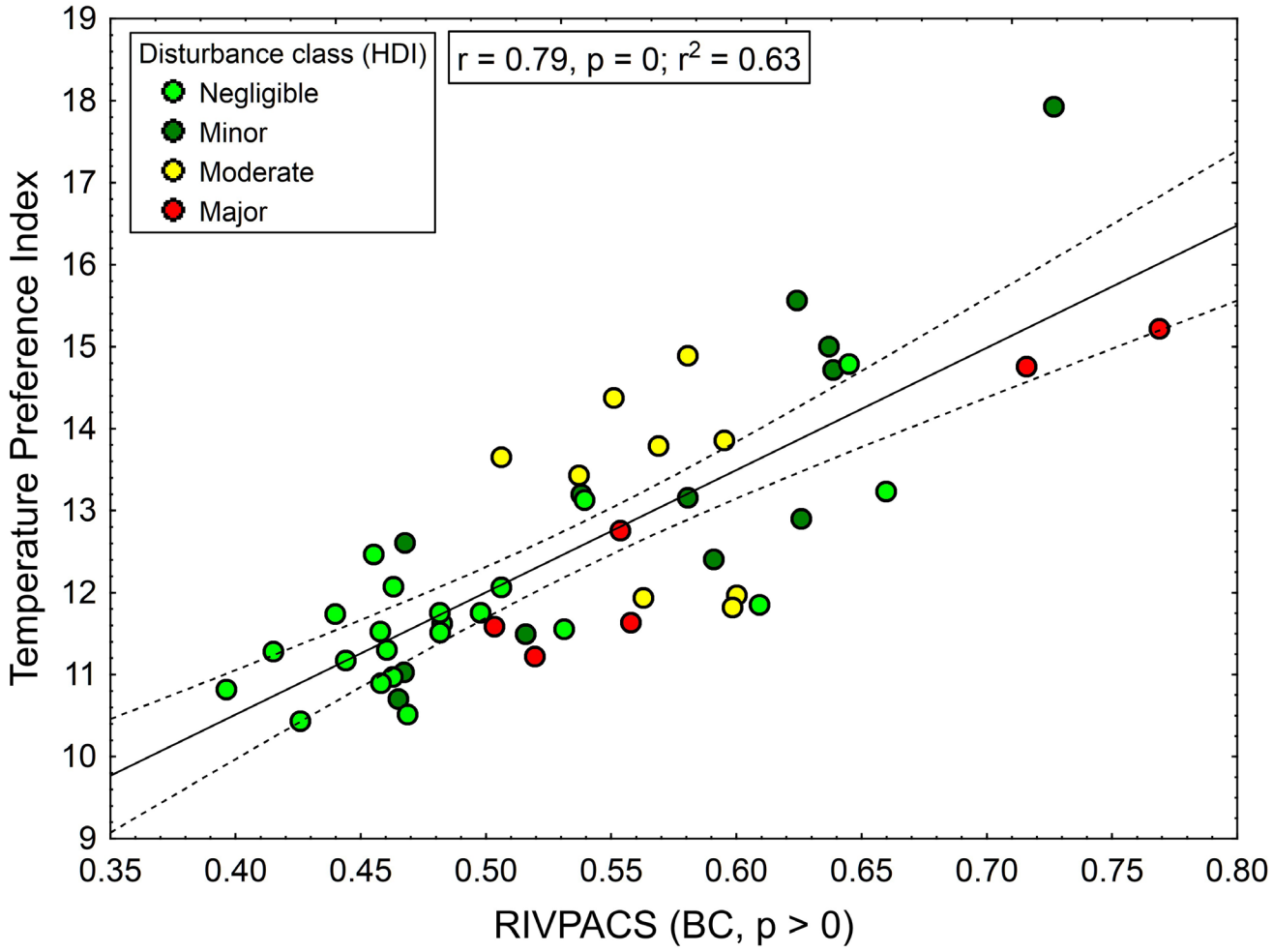


Figure 69. Linear bivariate model of the Temperature Preference Index (TPI) and the 2005 River Invertebrate Prediction and Classification System (RIVPACS) model (Bray Curtis measure) for all macroinvertebrate taxa (p (probability of capture) > 0) in Glacier National Park, 2007–2009. The RIVPACS model was developed by Montana Department of Environmental Quality. Points are classified by their ecological assessment point Human Disturbance Index score, with red color indicating the highest level of human disturbance.

an analysis using Montana data to examine the relationship between stream nutrient concentrations and benthic macroinvertebrate metrics (Li et al. 2009; Suplee and Sada de Suplee 2011). Among the metrics examined, HBI showed a sufficiently patterned response to stream nutrient gradients in Montana's mountainous regions that Montana DEQ uses it as a secondary response variable to help assess nutrient impacts (Suplee and Sada de Suplee 2011; Suplee and Watson 2013). Montana DEQ applied change-point analysis (Qian et al. 2003) to statistically derive a shift or threshold in HBI and nutrient concentrations.

HBI in Glacier ranges from about 1 to 7, with lower scores indicating a community more likely to persist in systems with nutrient concentrations. We use the Montana DEQ threshold (4.0) for the mountains bioregion in the state. From 2007 to 2009 the median HBI for the population of streams in Glacier was 3.4. About 70% of the stream had macroinvertebrate assemblages with few to no nutrient tolerant species, suggesting no or limited nutrient issues (Table 24). We treat this as a reference state with minor disturbance. Around 30% was in a non-reference state (with assumedly major disturbance levels). SEI survey methods do not quite match the required protocol for implementation of the Montana DEQ criterion, so these results should be used with caution. Note, however, that an HBI threshold of 4.0 closely matches ecoregional assessment point values, indicating that our results would be similar should we use the Montana DEQ assessment strategy.

Figure 70 shows the spatial pattern in HBI scores across the park. As with other indicators, select sites in or near the park's front country have higher scores (here above the

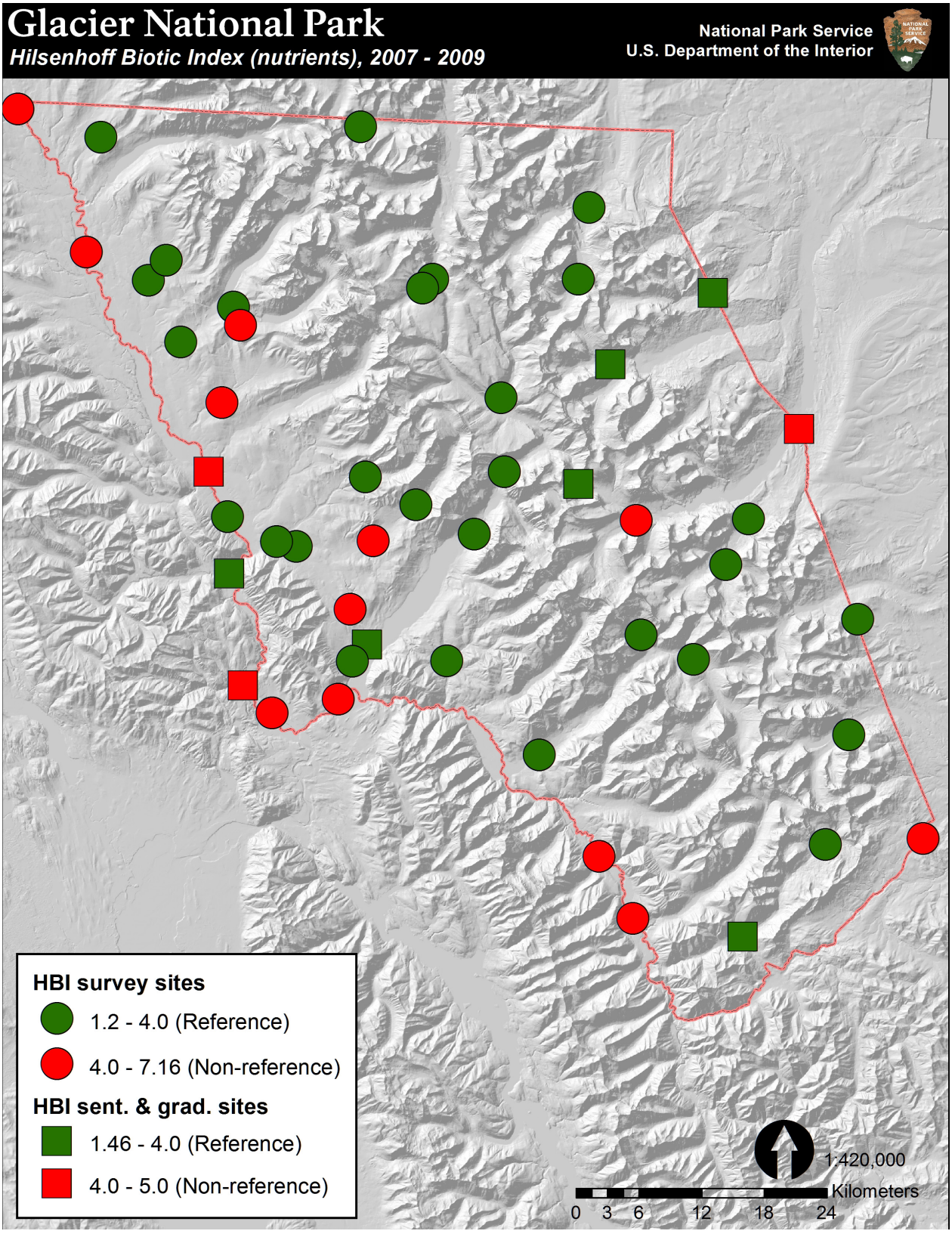


Figure 70. Map of Hilsenhoff Biotic Index (HBI) at Stream Ecological Integrity survey, sentinel (sent.), and gradient (grad.) sites in Glacier National Park, 2007–2009. Colored condition classes are based on a Montana DEQ criterion. Red color indicates sites with macroinvertebrate communities more tolerant of nutrients. See Appendix A for a complete list of site numbers and names.

Montana DEQ threshold), indicating potential issues with disturbance. However, with HBI, more sites have a suggested biological response to nutrients.

There are potentially meaningful patterns with nitrogen and phosphorous (see example in Figure 71) and HDI (Figure 72), suggesting that HBI may have a structural relationship with both nutrients and human disturbance and thus serve as a diagnostic tool of biological response to nutrients.

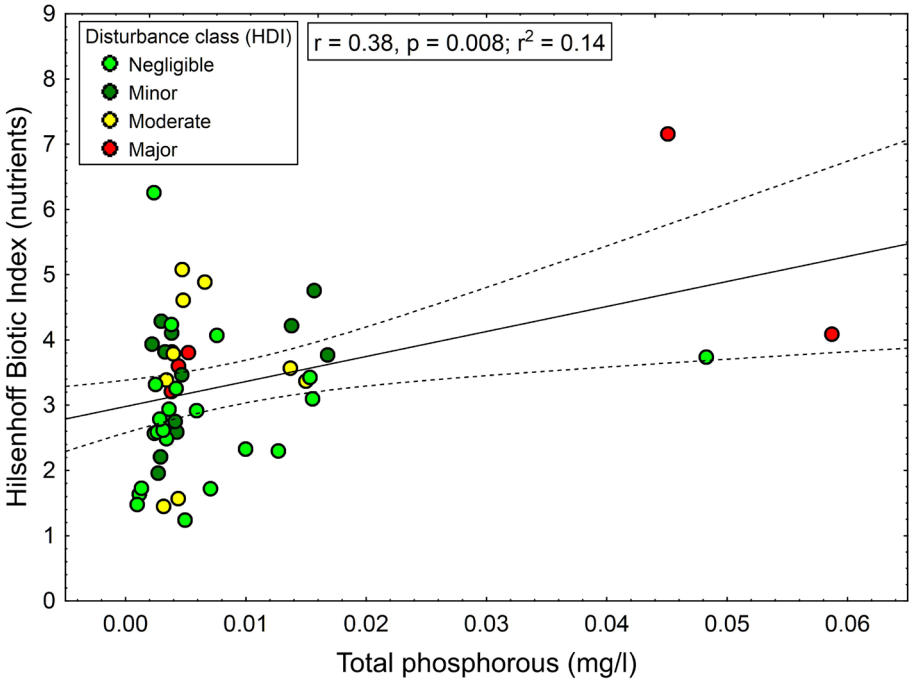


Figure 71. Linear bivariate model of the Hilsenhoff Biotic Index (HBI) and total phosphorous (mg/l, log) in Glacier National Park, 2007–2009. Points are classified by their ecological assessment point Human Disturbance Index score, with red color indicating the highest level of human disturbance.

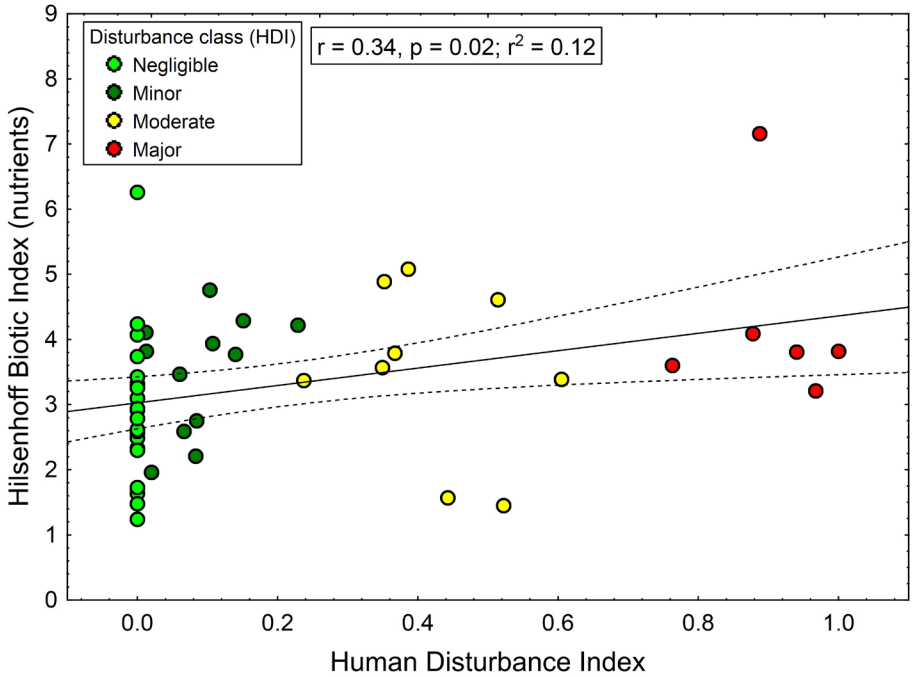


Figure 72. Linear bivariate model of the Hilsenhoff Biotic Index (HBI) and Human Disturbance Index (HDI) in Glacier National Park, 2007–2009. Points are classified by their ecological assessment point Human Disturbance Index score, with red color indicating the highest level of human disturbance.

Signal : noise

The S:N of most macroinvertebrate bioassessment metrics was acceptable, with the exception of O:E using common taxa ($p > 0.5$; Table 24). It is possible that with fewer taxa included due to excluding rare expected (E) species in this version of the model, it may be more likely that revisits to a site would not include the same taxa as in earlier visits. However, in general, these S:N values suggest that the bioassessment metrics in Glacier had higher precision.

3.8.3.2 Diatoms

Table 27 provides summaries of diatom park-scaled models developed for this report and existing large scale bioassessment models estimated using SEI data. These models are summarized and discussed in turn in the following sections.

Glacier National Park Diatom Multimetric Index (MMI_{Gd}): Estimation

We construct a diatom multimetric index specific to Glacier National Park (hereafter, Glacier Diatom MMI, or MMI_{Gd}; Table 27) from a set of 91 candidate metrics (Appendix D), HDI, and a suite of environmental covariates following Schoolmaster, Grace, and Schweiger (2012), Schoolmaster, Grace, et al. (2012), and Schoolmaster et al. (2013). An overview of the modeling process we use is provided with the macroinvertebrate model above.

Our final conceptual model (Figure 73) includes five covariates, each of which influence stream diatom communities. We consider environmental covariates to be relevant in the Glacier Diatom MMI if they have demonstrated relationships with diatom response in the literature and/or in our analyses of SEI Glacier data (see the human disturbance, water chemistry, and physical habitat sections above) – but not with human disturbance. Of the five covariates in MMI_{Gd}, distance to closest lake in Glacier may have no causal relationship with human disturbance (although human land use in less protected landscapes can increase near attractive lake shores). Maximum water temperature likely has a complex, largely indirect structural relationship with human disturbance and it likely unfolds over long time and spatial scales. In other systems, human disturbance can play a strong role in nutrient concentration; however, our model (see Table 12) of total phosphorous (which is strongly correlated with organic phosphorous) did not show any statistical connections with HDI in Glacier in 2007–2009. HDI can influence stream substrates, including the amount of fine gravel present at a site. We do not model fine gravel specifically in Glacier. Our predictive model of relative bed stability (correlated with fine gravel) showed that only 3% of the variation in bed stability was due to HDI. This may lead to some loss of predictive power in the Glacier Diatom MMI, but given the strong influence of substrate on diatoms, we felt this was an acceptable tradeoff.

The final Glacier Diatom MMI (Figure 74, Table 28) was selected from two statistically equivalent (i.e., each had similar correlation with human disturbance and were indistinguishable based on their AIC scores) candidate models using a comparison of the interpretability of their component metrics and a series of validation steps. As noted above, our MMI models create the best possible (in a statistical sense) index to the ecological integrity of Glacier's streams based on data used (Schoolmaster, Grace, and Schweiger 2012; Schoolmaster, Grace, et al. 2012; Schoolmaster et al. 2013). However, the approach may sacrifice some ability to interpret component metrics. This may be especially true for diatoms, where some metrics are themselves complex (see Schweiger, Grace, et al. 2016).

Glacier National Park Diatom Multimetric Index (MMI_{Gd}): Validation

We followed the same validation steps used with the macroinvertebrate MMI. In summary, this consisted of comparing models estimated using validation and calibration datasets. Validation models with the smallest change in adjusted r^2 and delta AIC from the calibration version suggest that the given model fits the data better. We also construct models that test for an effect of data source (calibration or validation).

As with the macroinvertebrate MMI, reductions in the adjusted r^2 and larger delta AICs from calibration to validation models were expected. Model variant 2 had the smallest changes (an adjusted $r^2 = 0.64$ for calibration to an adjusted $r^2 = 0.33$ for validation; AIC from 97.9 to 156.3 or a delta AIC of 58.4; Figure 75) and thus we assumed most consistently estimated the Glacier Diatom MMI. Model variant 2 also had component metrics that were generally interpretable. However, for both candidate Glacier Diatom MMI models, the data source (validation or calibration) was marginally significant, suggesting less successful validation than we saw with the macroinvertebrate model. Diatom communities are naturally variable and this may have driven this marginal result.

Glacier National Park Diatom Multimetric Index (MMI_{Gd}): Interpretation

The relationship of the final Glacier Diatom MMI with HDI was strong, with a negative correlation of -0.80 and an r^2 of 0.64 (Figure 74, Table 28). The fit between Glacier Diatom MMI and HDI is markedly better than with any of its individual component metrics (Table 28), confirming the statistical (and ecological) advantage and parsimony of an

Table 27. Summary of four 2007–2009 diatom based bioassessment metrics in Glacier National Park, 2007–2009.The probability of impairment values for the increaser models is the probability associated with the measured percent relative abundance for each group of increaser taxa. The assessment points for the increaser models are set by Montana DEQ as the percent relative abundance at the 0.5 level of probability of impairment.

Category	Bioassessment metric	Change with decrease in ecol. condition	Min. value from survey sites (all sites)	Park scale median	Max. value from survey sites (all sites)	LCL	UCL	Assessment points			Assess. point type	% of park streams in stressor class				Signal to Noise ratio (S:N)
								Major	Minor	Negligible		Major	Moderate	Minor	Negligible	
ROMN[1]	Glacier Diatom MMI (MMI_{Gd})	decrease	2.33 (2.16)	4.99	7.05	4.67	5.42	<3.44	4.87	>5.49[2]	ERG	12.2	32.1	28.3	26.5	1.9
Increaser models	N. Rockies sediment increasers PRA (%) [prob. impairment]	increase	1.0 [0.15]	7.7 [0.22]	34 [0.8]	5.6 [0.2]	7.9 [0.2]	>18.48[3]	–	–	–	3.1	–	96.9	–	2.8
Increaser models	N. Rockies nutrient increasers PRA (%) [prob. impairment]	increase	0.03 [0.2]	5.3 [0.28]	37 [0.95]	3.8 [0.2]	7.7 [0.3]	>15.18[3]	–	–	CRT	5.4	–	94.6	–	0.5
Increaser models	Mountain metal increasers PRA (%) [prob. impairment]	increase	0.03 [0.03]	5.2 [0.06]	39.8 [0.78]	4.6 [0.05]	6.2 [0.07]	>16.19[4]	–	–	CRT	9.1	–	90.9	–	2.0

Table Notes: Median and confidence intervals are derived from survey-design based estimation methods. Minimum and maximum values are at the site scale and (if meaningfully different) given for survey only sites and (in parentheses) all sites. Codes for assessment point types are: ERG = ecoregional assessment point and HDI = 0 based predicted Glacier Diatom MMI values, CRT = regulatory criterion. Note that where there is only one assessment point, there is no moderate class and we therefore lump moderate and minor categories and apply the color code from the minor class. The percentage of Glacier National Park streams in major/moderate/minor stressor classes was derived by comparing design-based results to assessment points. Some percentages are approximate as assessment points often fell between two values in the cumulative distribution and must therefore be interpolated. S:N was derived across all 49 sites and the 97 visits to these sites from 2007 to 2009. Problematic S:N values are below 1.0.

[1] Rocky Mountain Inventory and Monitoring Network.

[2] Ecoregional assessment points predicted from a model of Glacier Diatom MMI and HDI and the >95th percentile for major disturbance and a <75th percentile for minor disturbance values. A moderate disturbance class falls in between these values. For negligible, we use the predicted value at HDI = 0.

[3] State of Montana aquatic life support standards (Teply 2010a, b; Montana DEQ 2012b, 2017). As set by Montana DEQ the assessment point values are the percent relative abundance (PRA) where the probability of impairment is at or greater than 0.50.

[4] Historical State of Montana aquatic life support standards no longer used by Montana DEQ (Teply and Bahls 2005). Values are the PRA, where the probability of impairment is greater than 0.50.

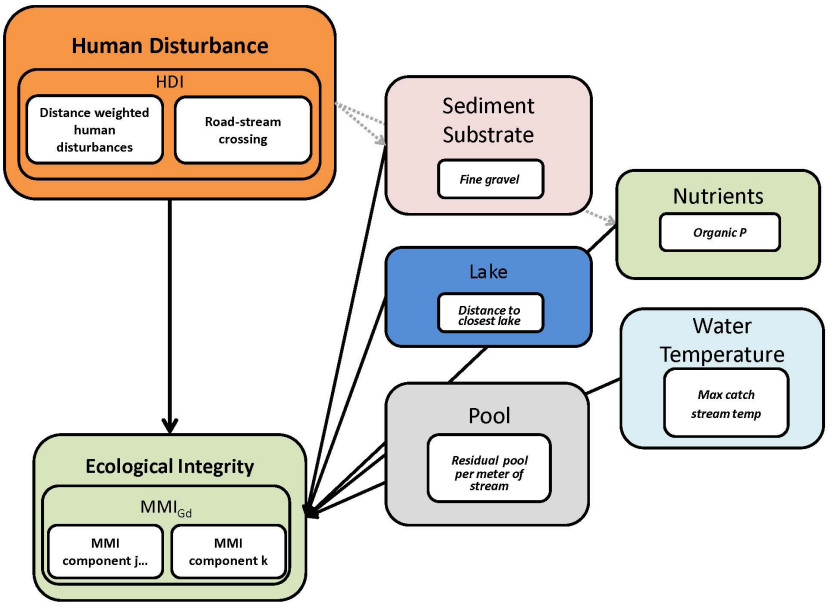


Figure 73. Conceptual model for Glacier Diatom Multimetric Index (MMI_{Gd}). Covariates included in the model are shown with solid boxes and arrows, with the assumed or demonstrated structural direction of a relationship indicated by the head of an arrow. Dotted faint arrow indicates possible structural connection between HDI and an environmental gradient, but one that, we assume, plays a minor role in Glacier National Park.

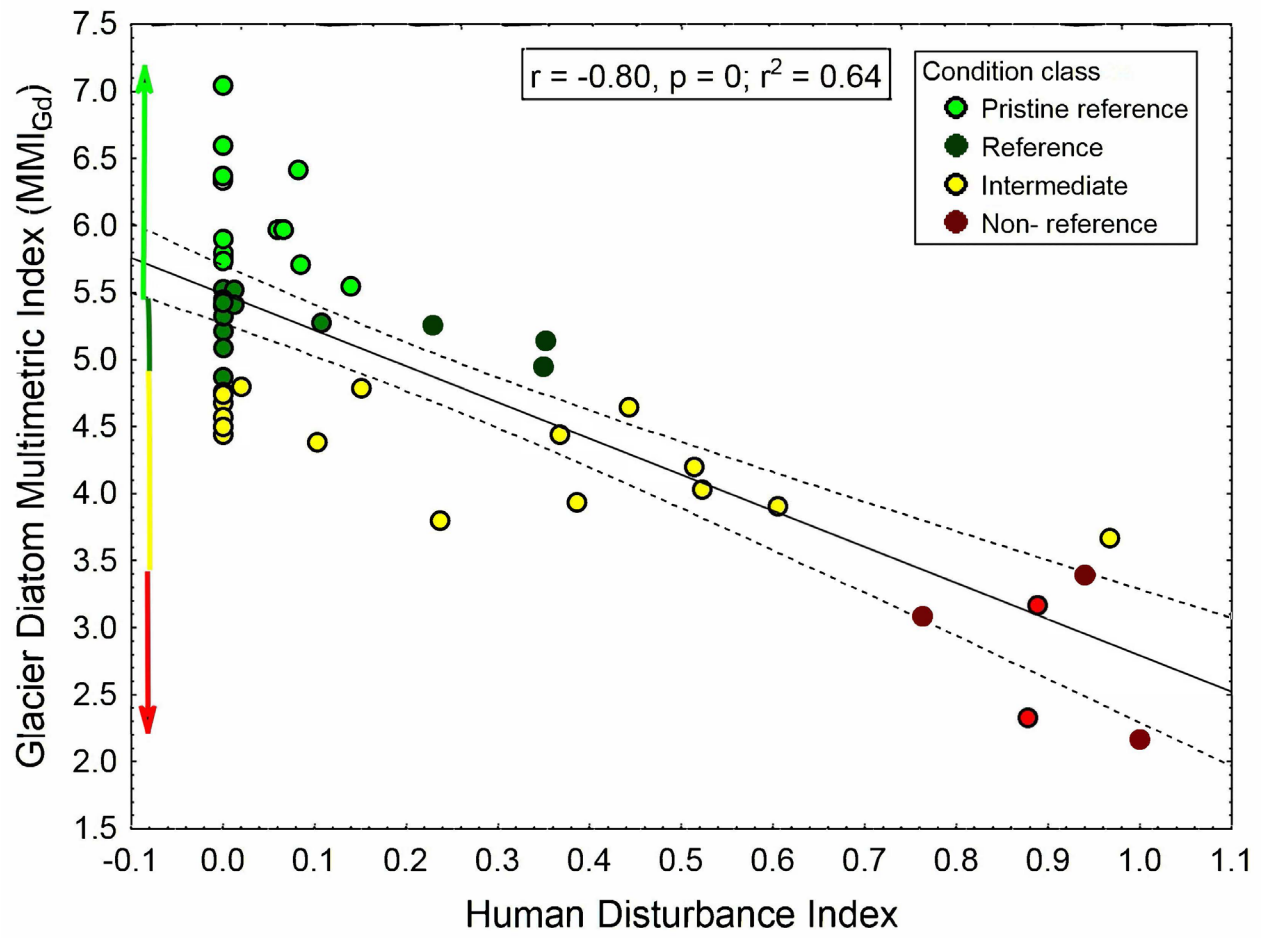


Figure 74. Bivariate relationship between Glacier Diatom Multimetric Index (MMI_{Gd}) and Human Disturbance Index (HDI), Glacier National Park, 2007–2009. Linear fit and its 95% confidence intervals indicated by black solid and dashed lines, respectively. Point symbology and vertical lines along Y axis derived from condition classes in MMI_{Gd} predicted from disturbance values in HDI at 0 (negligible disturbance, light green), 0.23 (minor disturbance from the 75th percentile of HDI, dark green) and 0.76 (major disturbance from the 95th percentile of HDI, red). Moderate disturbance or intermediate integrity falls between minor and major assessment points (yellow).

Table 28. Final component metrics of the Glacier National Park Diatom Multimetric Index (MMI_{Gd}). Table includes correlation (r) for each metric with HDI before and after scaling/adjustment by the coefficients and intercept as shown for each covariate in the model. Positive correlations with human disturbance (HDI) are shown in green, and negative correlations are shown in red. PRA is percent relative abundance.

Metric Name	r (raw)	r (adjusted, scaled)	Intercept	HDI	Max stream temp	Fine gravel	Lake effect	Pool	Organic phosphorous
Oxygen demand PRA	-0.27[1]	-0.26[1]	0.47	-0.16	0.00	0.00	0.00	0.00	0.00
Brackish PRA	0.36[2]	0.36[2]	0.73	0.14	0.00	0.00	0.00	0.00	0.00
Staurosirella richness	-0.15[1]	-0.39[1]	-0.34	-1.33	0.19	0.06	0.00	-16.58	0.00
Nitzschia richness	0.20[2]	0.24[2]	-4.32	1.71	0.50	0.18	0.00	0.00	253.88
Pseudostaurosira PRA	-0.12[1]	-0.33[1]	0.03	-0.02	0.00	0.00	0.00	-0.32	0.00
Fragilaria PRA	0.06[2]	0.19[2]	0.02	0.02	0.00	0.00	0.06	0.00	0.00

[1] Negative correlation with human disturbance (HDI).

[2] Positive correlation with human disturbance (HDI).

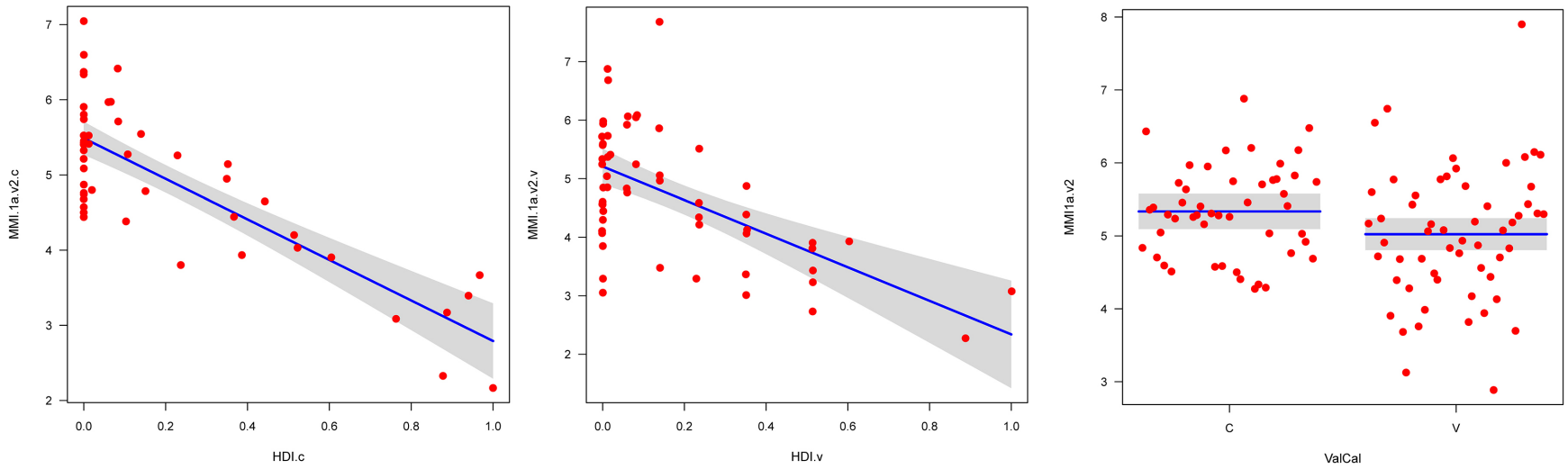


Figure 75. Calibration (MMI1a.v2.c) and validation (MMI1a.v2.v) bivariate models for the Glacier Diatom Multimetric Index (MMI_{Gd}). Models are developed from assumed independent datasets. Linear fits and their 95% confidence intervals are shown with the blue line and gray shaded regions. The third panel shows calibration (C) and validation (V) data as points with a mean (horizontal blue lines) and 95% confidence intervals (gray shaded boxes).

MMI. Most component metrics had at least one meaningful relationship with a covariate and adjustment improved the signal in all cases, confirming that controlling for these environmental gradients improved the model (Schoolmaster, Grace, and Schweiger 2012; Schoolmaster, Grace, et al. 2012; Schoolmaster et al. 2013).

The final Glacier Diatom MMI (Table 28) includes six component metrics within four classes: oxygen demand, salinity tolerance, taxonomic richness, and taxonomic composition. When combined in the Glacier Diatom MMI, these metrics are integrative of the suite of underlying ecological processes and/or responses to human disturbance in the streams of Glacier. However, interpreting component metrics can support insight into relationships between diatom integrity and human disturbance. Of the six component metrics, two are measures of general tolerance to autecological conditions (oxygen saturation and salinity). These both follow generally intuitive patterns: first, a decrease in taxa requiring continuous and high levels of oxygen saturation was associated with human disturbance (which can reduce oxygenation levels), and second, an increase in taxa tolerant of higher salinity, which can also be caused by human use of a system. The remaining four metrics are either changes in richness or relative abundance of species within specific genera. While interpreting across species can be complex, oftentimes autecological responses are consistent at the general level. Stoddard et al. (2005) show that the relative abundances of many *Staurosirella* species in western US streams and rivers are negatively related with general measures of human disturbance. Species in the *Nitzschia* genus have a complex relationship with human disturbance, although many taxa are tolerant of higher salinity, metal concentrations, and organic pollution (Palmer 1969; Lange-Bertalot 1979). For example, *Nitzschia dissipata* (Figure 76) was common at the Railroad Creek site, which was well documented in this report as one of the few sites in the park with meaningful human disturbance. The changes in richness we see with increasing HDI in Glacier's streams with these two genera may reflect these patterns. Stoddard et al. (2005) also show a negative relationship between most *Pseudostaurosira* species and human disturbance – generally matched in 2007–2009 SEI data. Likewise Morales (2005) indicates that many *Pseudostaurosira* species prefer lower nutrient concentration and moderate to low specific conductance – both of which generally increase with human use of a stream (although these patterns are subtle in Glacier). Finally, while Lange-Bertalot (1979) and Morales (2005) suggest several species in the *Fragilaria* genus have lower tolerances for organic pollution, some species that occur in Glacier, such as *Fragilaria capucina*, are in contrast generally tolerant (Chaffin et al. 2012). This species is actually a candidate for biofuel production given its high tolerance for nutrients and temperature and thus greater resilience to disturbance. Overall, the relative abundance of *Fragilaria* increased with HDI in SEI samples from Glacier due to taxa like *F. capucina* with this form of response.

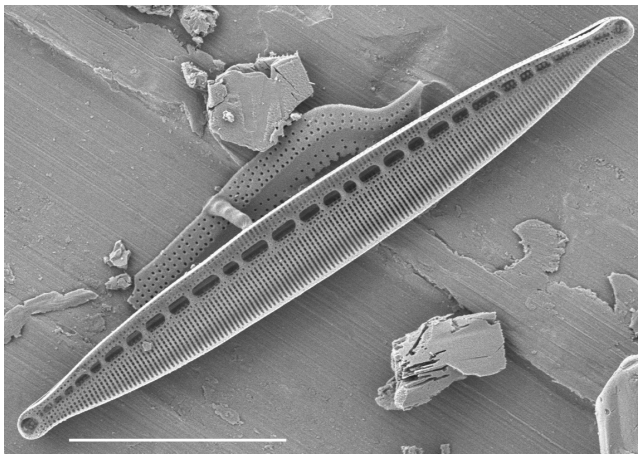


Figure 76. *Nitzschia dissipat*a (scanning electron microscope view at 10 um). This species is more tolerant of human disturbance and was relatively common at the Railroad Creek site, which was well documented in this report as one of the few SEI sites with meaningful human disturbance. Image credit: Eduardo Moralies. Image source: Manoylov, K. 2010. *Nitzschia dissipata*. In Diatoms of North America. https://diatoms.org/species/nitzxchia_dissipata.

Glacier National Park Diatom Multimetric Index (MMI_{Gd}): Spatial pattern

The spatial pattern of the Glacier Diatom MMI (Figure 77) resembles many of the other distributions we report for 2007–2009 stream sites in Glacier. As with all ecoregional assessment point based classifications, these are relative and should be used with caution. This is especially so for our custom MMI models as the ecoregional reference site population is restricted to SEI sites alone. However, we have confidence in Glacier Diatom MMI scores in the pristine reference class as these correspond to streams with no measurable human disturbance – a condition which we consider ecologically meaningful. In general, most wilderness sites in the interior of the park had this pristine state designation. Yet there were perhaps more sites in an intermediate state than we might expect (again based on ecoregional assessment points). Unless there is also meaningful human disturbance at these sites (and with the exception of a site on McDonald Creek, see Figure 17 and Figure 25, there is no meaningful disturbance at these sites), we do not consider this to be of concern. While the modeling process should

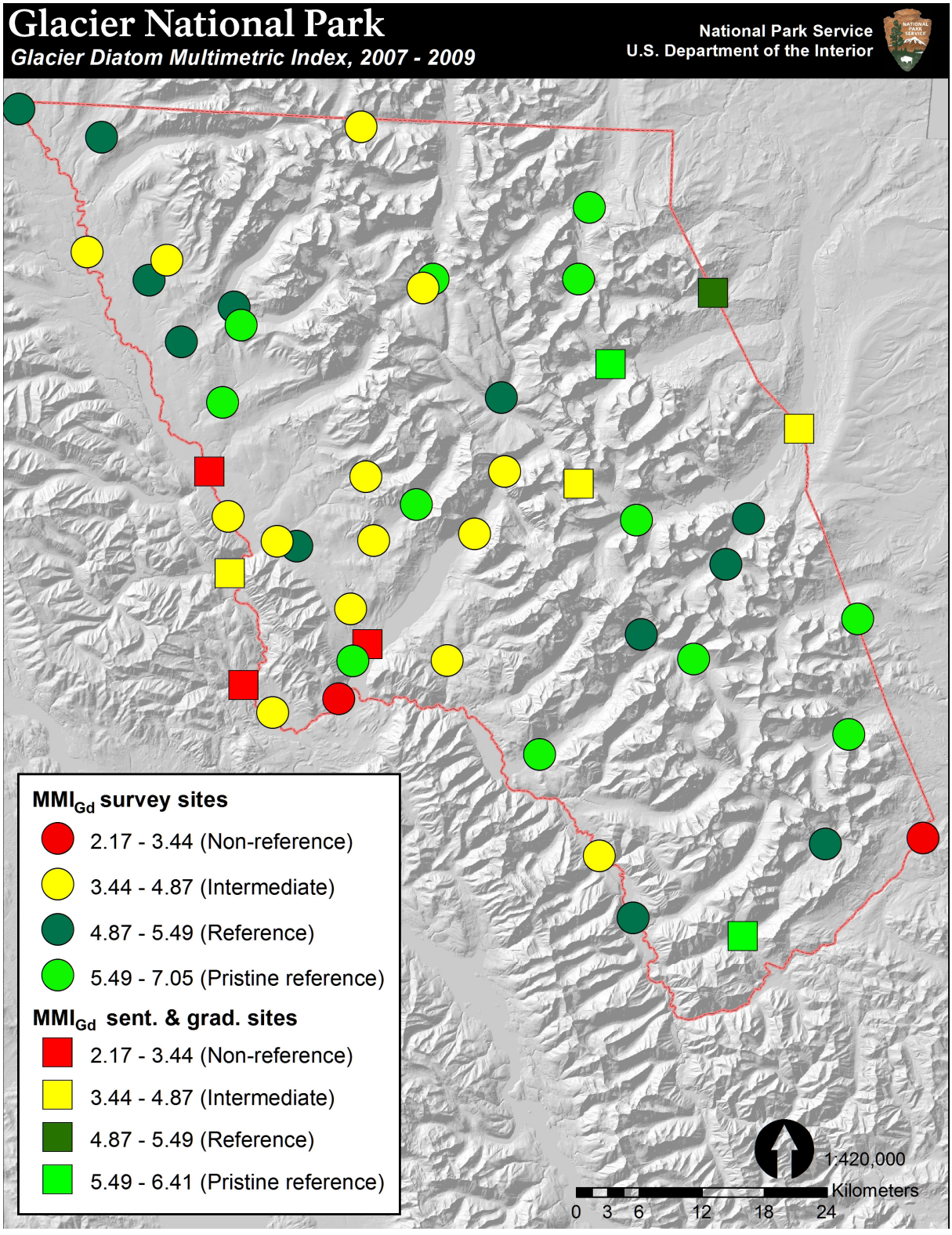


Figure 77. Map of Glacier Diatom Multimetric Index (MMI_{Gd}) at Stream Ecological Integrity survey, sentinel (sent.), and gradient (grad.) sites in Glacier National Park, 2007–2009. Colored condition classes are based on ecoregional assessment points predicted from a model of MMI_{Gd} and HDI and the >95th percentile for major disturbance (red dots) and a <75th percentile for minor disturbance (dark green dots). A moderate disturbance class falls in between these values (yellow dots). For the negligible disturbance class we use the predicted Glacier Diatom MMI value at HDI = 0 (light green dots). See Appendix A for a complete list of site numbers and names.

have accounted for most natural sources of variation, it is possible these sites have relatively intact communities that happen to resemble those seen in more clearly human impacted sites. Additional work will be needed to resolve this. We do see lower diatom based ecological integrity at many stream sites on the boundaries of the park and along visitor services corridors. For example the Railroad Creek and Rubideau Creek tributary sites, along with some of the tributaries to the North Fork of the Flathead (Coal Creek, and Canyon Creek) were in a non-reference class based on diatom community structure. Of note, the Glacier Diatom MMI appeared more responsive to general human disturbance relative to stressor specific diatom increaser models (see subsection after Glacier Diatom MMI Inference, below). An MMI model has the advantage of estimating a synthetic response or a general condition state not restricted to a single stressor type. While this may not produce diagnostic results, it is well suited to our objectives of estimating ecological integrity.

Glacier National Park Diatom Multimetric Index (MMI_{Gd}): Inference

Design-based summaries infer Glacier Diatom MMI results to all sampleable Glacier streams in 2007–2009 (Figure 78). The median MMI_{Gd} for the population of streams in Glacier was 4.99 (Table 27). Roughly 12% (with a 95% confidence interval of 0–25%) of the streams in the park had Glacier Diatom MMI values below 3.44 (as predicted from a major HDI score of 0.76) and were in a non-reference condition. Around 28% percent of park streams were in a reference state, and around 27% (58-89%) were above a Glacier Diatom MMI score of 5.49 and in a pristine reference condition (corresponding to a HDI score of 0). The ability to further classify reference streams into this "best of the best" state

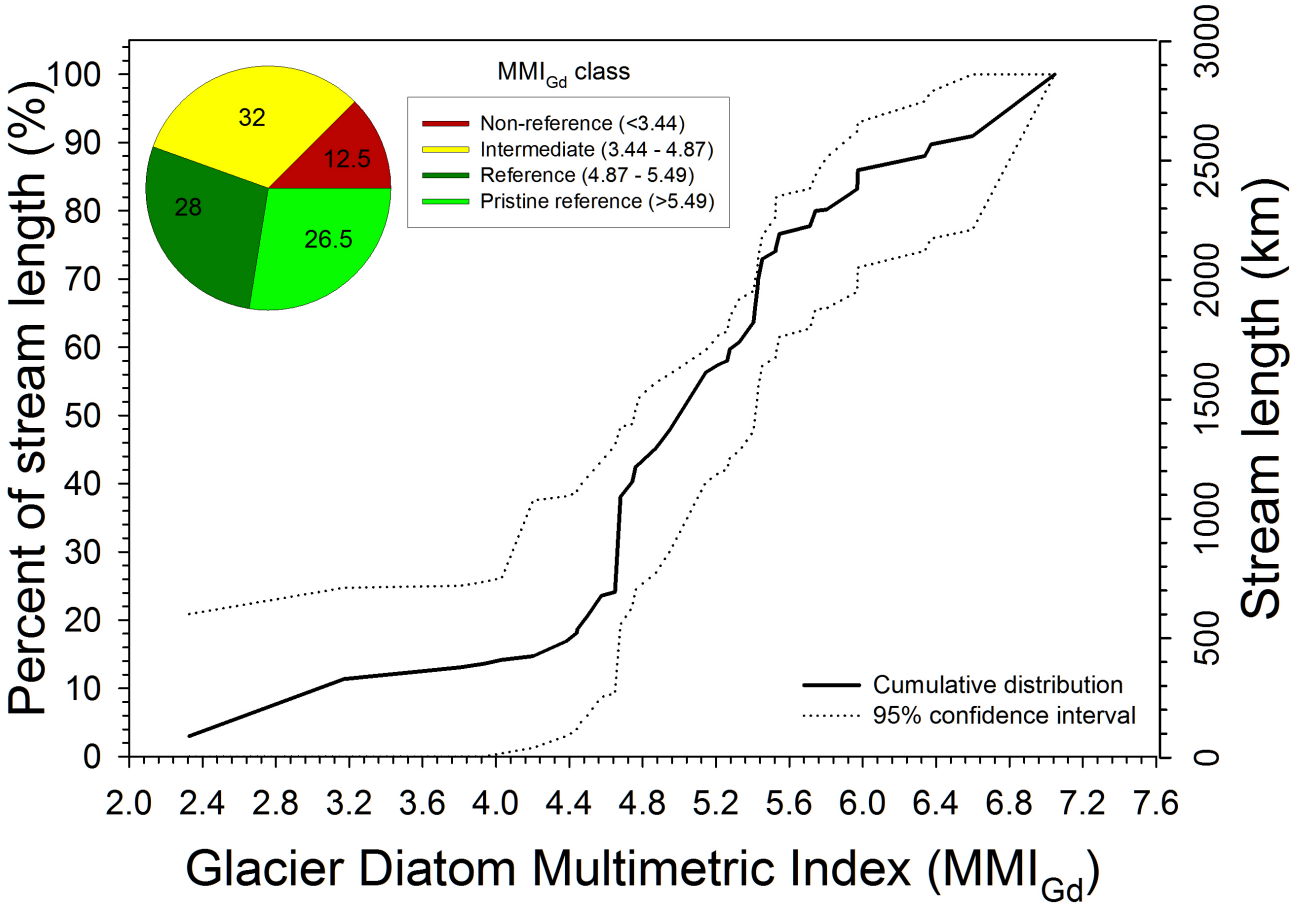


Figure 78. Cumulative distribution of Glacier Diatom Multimetric Index (MMI_{Gd}) in the population of Glacier National Park streams, 2007–2009. The left y-axis gives the percent of streams in the park and the right y-axis shows the actual estimated length of stream. A 95% confidence interval (dotted lines) around the percent values (heavy line) is also shown. Pie chart shows the percentage of the total length in pristine reference (light green), reference (dark green), intermediate (yellow), and non-reference (red) condition classes based on predicted assessment points from a model of Glacier Diatom MMI and HDI. Pie charts do not include a confidence interval for each estimate in these classes, so they should be used with caution.

is unique to our MMI models and one of the strengths of the approach. The remainder of park streams (around 32%) were in an intermediate condition. These values are generally similar to many other metrics of condition, showing a relatively small percentage of the park's streams in non-reference condition. As noted above, we have stronger confidence in Glacier Diatom MMI scores in the pristine reference class, as these correspond to streams with no measurable human disturbance – a condition which we consider ecologically meaningful and we believe corresponds to the desired condition of Glacier streams in the wilderness and rustic management zones of the park (NPS 1999).

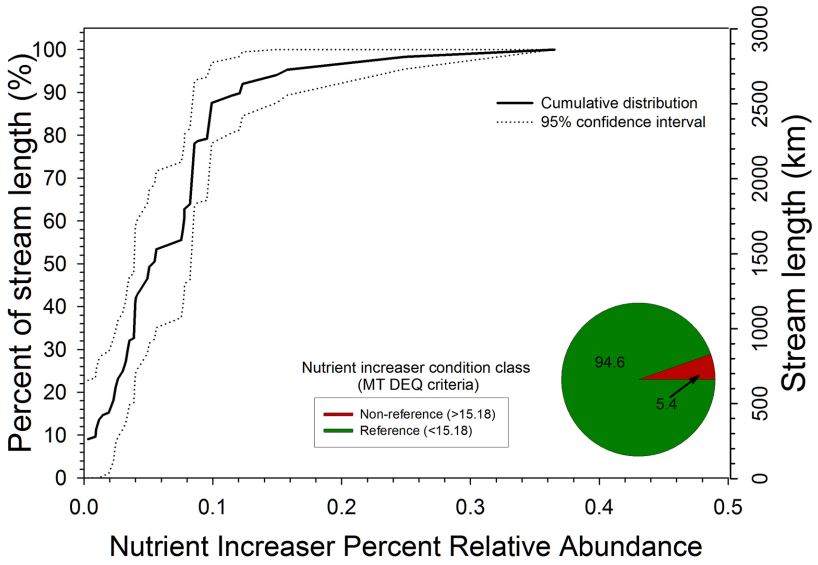
Existing diatom increaser models applied to Glacier National Park

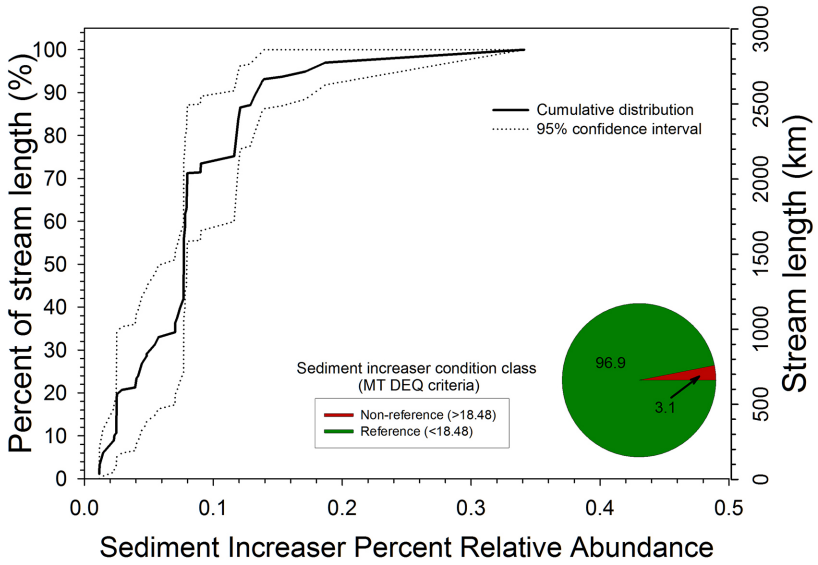
The State of Montana has been using diatoms to assess water chemistry in wadeable streams since the 1970s (Bahls et al. 2008). Early efforts were based on Shannon diversity (Weber 1973), autecological tendencies compiled by Lowe (1974), and the pollution tolerance classes of Lange-Bertalot (1979). Beginning in the early 2000s Teply and Bahls (2005, 2006) and Teply (2010a, b) developed diatom based bioassessment "increaser" models. Increaser models identify taxa that, as a group, exist in detectable amounts in a given stream class and demonstrate a meaningful, measurable, and significant response to fine sediment, nutrients, or metals. Taxa unique to these cause-specific lists are considered ecological specialists that are tolerant of that cause. Increaser taxa are derived from empirical observations across a large number of streams classified by ecoregion and type of impairment. The models identify taxa based on increases in average abundance in the presence of a stressor and then use discriminant functions to estimate the probability of impairment given these percent relative abundances (PRA). Criteria were set by Montana DEQ based on a percent relative abundance at or above a 50% probability of impairment for sediment, nutrients, or metals. Should Montana DEQ ever need to assess stream(s) in Glacier using increaser metrics, the network will work with them in the application of these tools to the park's streams and rivers. Of particular concern, the increaser metric for metals was developed for a broader scale "mountain bioregion" and Montana DEQ does not currently use this model for regulatory issues. The model is not as robust as the current ecoregion specific sediment and nutrient versions, so it is used with caution.

Increaser models provide an interesting and useful complement to our more general Glacier Diatom MMI largely because, much like the stressor specific macroinvertebrate metrics, they may be more diagnostic of particular threats to the park's streams. We therefore estimated each of the diatom increaser metrics using 2007–2009 Glacier SEI data. These results suggest that a small percentage of the sampleable stream in the park (Table 27, Figure 79) had percent relative abundances of diatoms above the Montana DEQ criteria for impairment based on sediments (~3%), nutrients (~5%) or metals (~9%). We classify sites and the corresponding length of stream in the park above these PRAs as in non-reference condition. However, as discussed below for sediments and nutrients, it is likely that these sites are misclassified and the estimates of non-reference streams due to these stressors is actually lower. There are no assessment points for other classes (i.e., pristine reference) and we do not develop ecoregional assessment points for these metrics.

Figure 80 shows the spatial distribution of the three diatom increaser metrics across the park. For sediments and nutrients, the only sites with percent relative abundances of diatoms tolerant of these stressors above the Montana DEQ criteria of a 50% probability of impairment were at remote wilderness sites. With the exception of one site on lower Camas Creek with moderate human disturbance and more diatom nutrient increasers than the Montana DEQ criteria allow, these sites have negligible human stress (HDI = 0). There are some higher levels of nutrients at some of the sites but none with a clear human source. We expect these sites were misclassified by the respective models. For metals, we see a pattern similar to many other metrics, with possible concerns at select sites on boundaries of the park and along visitor services corridors (i.e., tributaries to Railroad and Rubideau Creeks, where runoff from nearby roads often contains metals). Most backcountry wilderness streams had reference caliber diatom community composition relative to taxa tolerant of metals. A few did appear to be misclassified, as with the nutrient and sediment models. As noted above, the metal increasers model is less robust than the other two and these results should be viewed with caution.

Note that increaser taxa do not discriminate other causes of a non-reference state and these results do not indicate whether the streams of the park may or may not be impaired due to other causes. Unlike the MMI models, these metrics are not generalized and should not be interpreted as relevant to overall stream integrity. However, given the lack of numeric State of Montana criteria for sediment and the complexities associated with direct chemical monitoring of nutrients, these results offer an important piece of evidence in the assessment of SEI data from Glacier. Excess sediments and nutrients are serious issues in Montana, with about half of the impaired streams in Montana impacted by sediment (Teply 2010a, b).





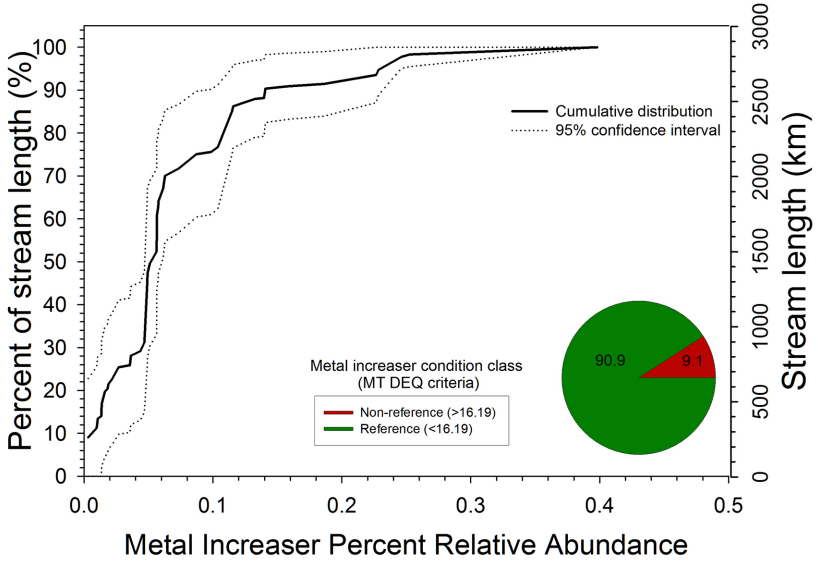


Figure 79. Cumulative distributions for Montana Department of Environmental Quality (MT DEQ) diatom increaser models for sediments, nutrients, and metals in the population of Glacier National Park streams, 2007–2009. The left y-axis gives the percent of streams in the park and the right y-axis shows the actual estimated length of stream. A 95% confidence interval (dotted lines) around the percent values (heavy line) is also shown. Pie chart shows the percentage of the total length in reference (dark green), and non-reference (red) condition classes based on comparisons with Montana Department of Environmental Quality criteria. Pie charts do not include a confidence interval for each estimate in these classes, so they should be used with caution.

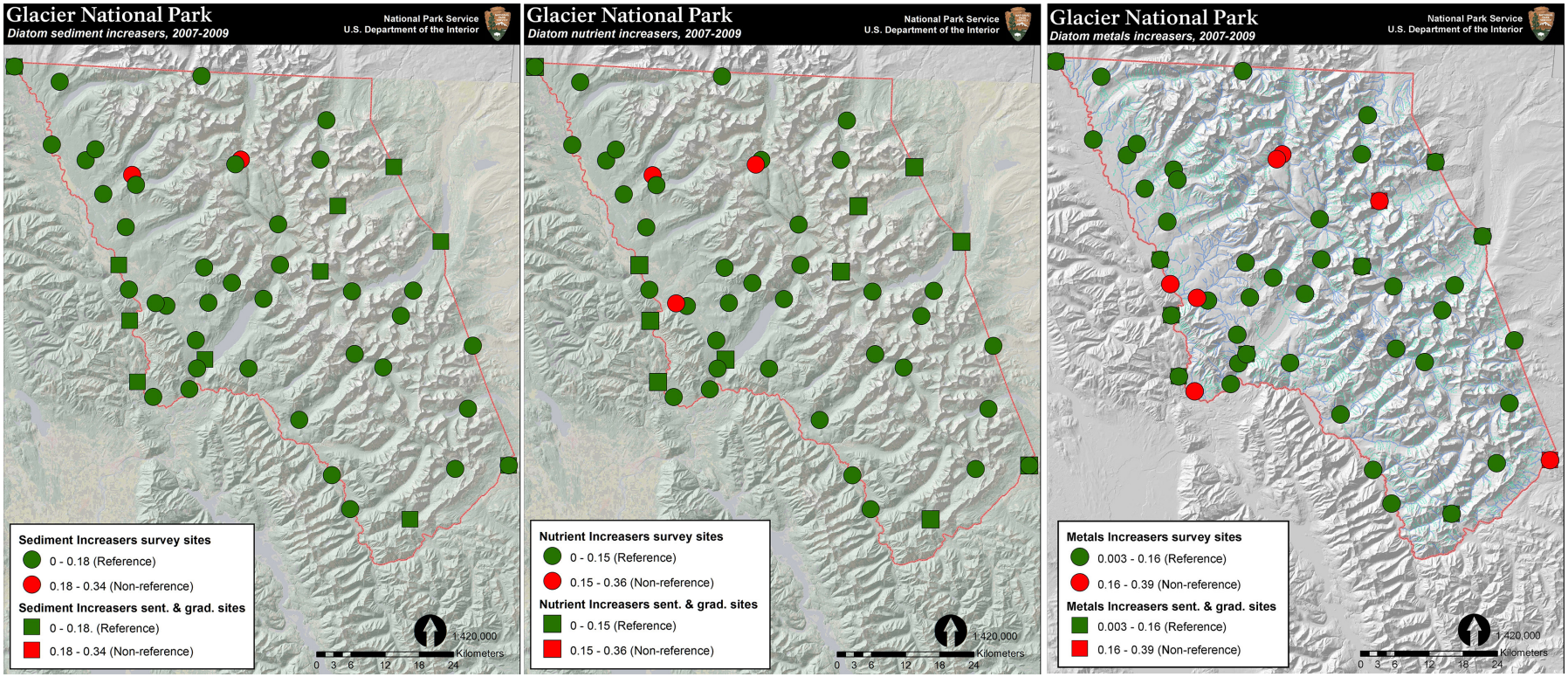


Figure 80. Maps of Montana Department of Environmental Quality diatom increaser metrics for sediments, nutrients, and metals at Stream Ecological Integrity survey sites and sentinel (sent.) and gradient (grad.) sites in Glacier National Park, 2007–2009. Colored condition classes are based on comparisons with Montana Department of Environmental Quality criteria, with dark green points in reference condition and non-reference condition in red. See Appendix A for a complete list of site numbers and names.

Existing diatom sediment increaser model: Exploratory model applied to Glacier National Park

Next, we present an exploratory model of diatom increasers. We chose sediment as the best response to model for four reasons: 1) we expect fine sediments are likely a greater concern in Glacier (vs. nutrients and metals), 2) a lack of Montana DEQ criteria for sediments, 3) the widespread problems with sediments in Montana streams, and 4) the more normal distribution of these data (relative to the nutrient or metal increaser metrics). Note that we don't model Glacier Diatom MMI, as our MMI methods account for natural gradients and multivariate relationships within the response of diatoms to human disturbance. We selected potential independent variables for the sediment increaser model based on our collective ecological experience, statistical attributes, and those that might also have the most utility for stream resource management in Glacier. For additional details on model construction see the methods, Appendix D, and/or the introduction to this same subject within the human disturbance section (3.5.4) above.

The final model of sediment increasers included six independent variables (Table 29). It was highly significant ($p < 4.434e-07$) with an adjusted r^2 of 0.55, indicating a meaningful proportion of the variation in sediment increasers was accounted for by the model. Complete model details are presented in Appendix F. We focus our interpretation here on select independent variables that either had high relative importance, low p-values, and/or interesting relationships as drivers or covariates of sediment increasers. We use conditional plots of partial residuals (Figure 81) to visualize the model (Larsen and McCleary 1972; Breheny and Burchett 2013).

Nearly 60% of the variation in sediment increasers was due to the concentration of organic phosphorous at the sampled sites. Many diatom taxa are well known to respond to this important nutrient (Cembella et al. 1982). This mirrors a pattern we saw with overall diatom community structure responding to organic phosphorous (Figure 56). The partial residuals plot suggests this is in large part driven by a large outlier (Figure 80 and Figure 79; the tributary to Bowman Lake site). However, with this removed, the relationship is still present and the Bowman Lake site's high phosphorous concentration is natural and likely due to a large wetland complex just upstream from the site. This site also had high scores for the nutrient increaser metric and high nitrogen and phosphorous loads. The site lacks high levels of fine sediment. The two lists of increaser taxa do overlap by 10 diatom species (Teply 2010a, b), likely explaining the pattern. The next most important predictor was the percentage of fine gravel at a site. Nearly all diatoms that live on sediments are highly motile (Crumpton 1989). Motile species are adapted to holding their position on unstable substrates, so the proportion of motile species or individuals in a sample may be directly related to the degree of sedimentation (in our model the percentage of fine gravels) on the stream bottom (Werner 1977). Overall, and perhaps most importantly, our model reveals no relationship with any sort of human disturbance signal at our sampled sites. This matches our general assessment of spatial patterns across sites and suggests that the sediment increaser metric in the park may be misclassifying diatom communities as increasers at a small number of sites with natural levels of sediments or as a response to naturally occurring nutrients. Thus, while there is value in applying this metric (and likewise the nutrient and metal increasers) to the park in that they likely show few diatom community responses to these specific stressors (where we think a site is properly classified), this must be treated with caution.

Table 29. Model of sediment increasers in the streams of Glacier National Park, 2007–2009. Final model selected using Akaike Information Criterion (AIC) and expert opinion from 26 candidate variables. Relative importance (Rel. Imp. %) is the total amount of explained variance for each variable expressed as a percentage.

Model component	Estimate	SE	t	p	Rel. Imp. (%)
Intercept	0.250	0.108	2.321	0.025	–
Burn (%, log)	-0.010	0.005	-2.245	0.030	0.041
Latitude (UTM)	-9.379E-07	3.391E-07	-2.766	0.008	0.118
Distance to closest Lake (m, log)	0.010	0.005	2.064	0.045	0.050
Organic phosphorous (mg/l)	10.760	1.754	6.137	2.520E-07	0.578
Fine gravel (%)	0.003	0.001	2.870	0.006	0.134
Pool	-0.448	0.212	-2.111	0.041	0.079

Notes: SE = standard error of coefficient, t = t test value, p = probability of the t. Residual standard error: 0.047 on 42 degrees of freedom, Multiple R^2: 0.59, Adjusted R^2: 0.54, F-statistic: 10.5 on 6 and 42 DF, p-value: 4.434e-07.

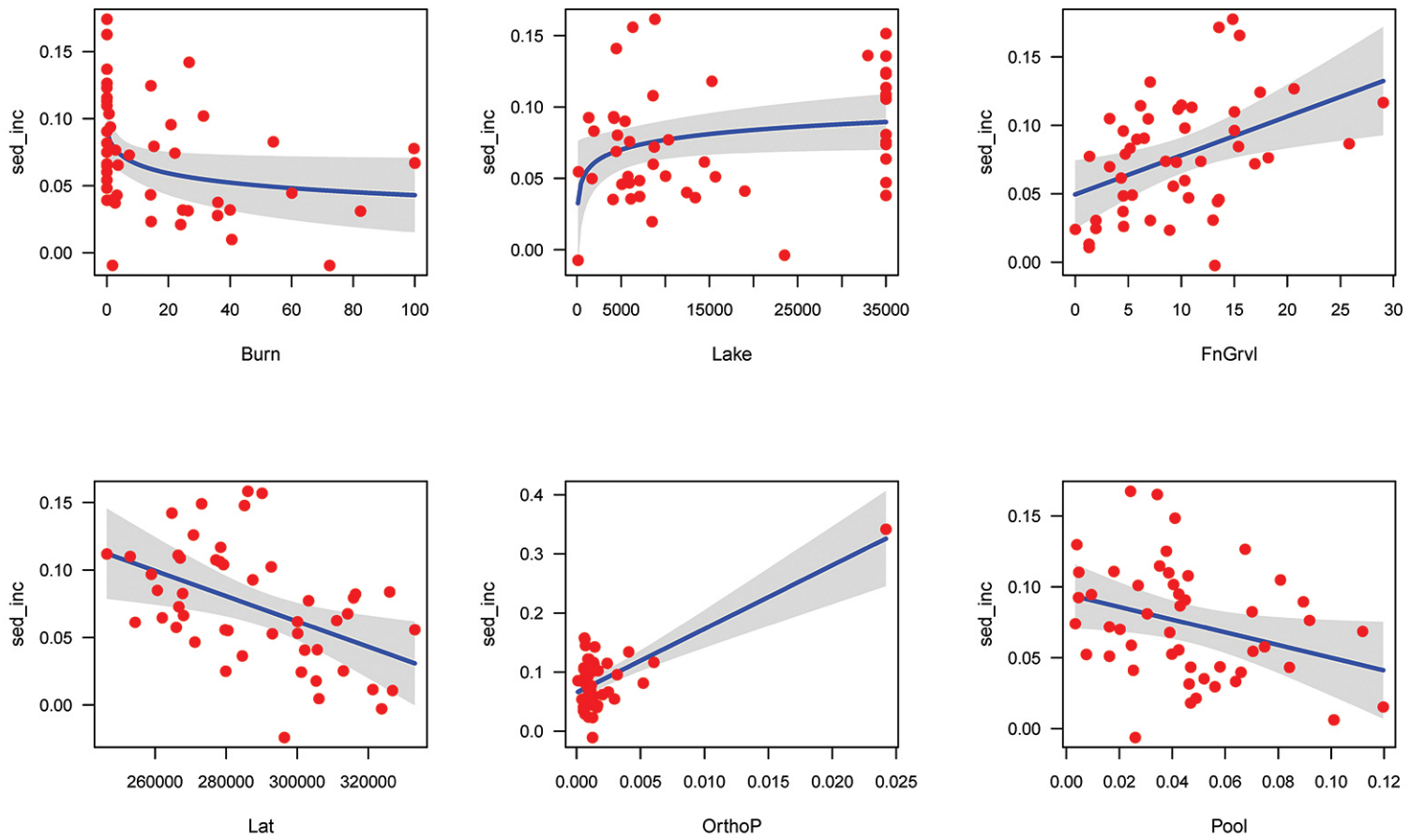


Figure 81. Partial residual plots of predictors of sediment increasers in Glacier National Park, 2007–2009. Conditional partial residuals show the relationship between each unique predictor and sediment increasers with all other variables held constant at the median. All variables are shown back transformed to their original scale as applicable. Plots of numeric predictors include a best fit line and 95% confidence bands around this fit. Codes in figures are: sed_inc = sediment increasers; Burn = percent of site's catchment burned since 1984; Lake = stream distance to closest lake outlet (m); FnGrvl = fine gravel (%); Lat = latitude; OrthoP = organic phosphorous (mg, l); Pool = density of pools. See the full model results in Appendix F and Table 29.

3.8.3.3 New to science diatoms

A large scale survey like the network and our partners conducted in 2007–2009 provides two interesting and useful auxiliary results: a list of new to science species and information on aquatic invasive species currently and potentially important to park resource management.

As of this report's publication date, we have documented 46 taxa previously undescribed in the scientific literature (Table 30, Figure 82). This is out of almost 500 total diatom species in our dataset. The new species are distributed across 14 genera. Most of the new taxa were only found once at one site. However, they occurred across a broad diversity of stream types, elevations, and macrohabitats. Ongoing work will better describe the community associations and key environmental drivers of these species.

In some sense, it is not unexpected to find new species of diatoms in Glacier. Many SEI sites are in locations that have never been sampled before. However, this does not diminish the implications of these new species. Most of these species are likely to be rare endemics, or species that occur only in a specific subset of streams in the world. Moreover, they also are likely highly responsive to climate change and indicative of the pristine condition characteristic of most of the park's streams. Therefore, they likely have value as indicators of stream condition in the park. Finally, they support Glacier as a repository of biological diversity that we should continue to protect and preserve for the benefit of science and the public at large.

3.8.4 Aquatic invasive species: detailed results and interpretation

Aquatic invasive species (AIS) can have profound effects on streams and rivers and are thus of concern for Glacier resource management. While the sample design of SEI monitoring is not explicitly geared towards collecting data on AIS, our larger sample size and unbiased design can provide useful data to help the park understand potential occurrences of important AIS. Given constraints in our design, SEI data should not replace more focused efforts to monitor Glacier for these species.

3.8.4.1 Zebra and quagga mussels

Zebra and quagga mussels are small shellfish native to Eastern Europe. Zebra mussels were first discovered in North America in the late 1980s in the Great Lakes. Zebra mussels represent one of the most important biological invasions into North America (Benson et al. 2017a). By 2010, they had spread across the Northeast and Southwest United States. Among their many negative impacts, zebra mussels cause serious biofouling by colonizing water supply pipes of hydroelectric and nuclear power plants, public water supply plants, and industrial facilities. Zebra mussels can have profound effects on ecosystems. Large populations of zebra mussels in the Great Lakes reduced the biomass of phytoplankton significantly following invasion. Diatom abundance declined 82–91% and transparency, as measured by Secchi depth, increased by 100% during the first years of the invasion in Lake Erie (Holland 1993). Biomagnification of Polychlori-

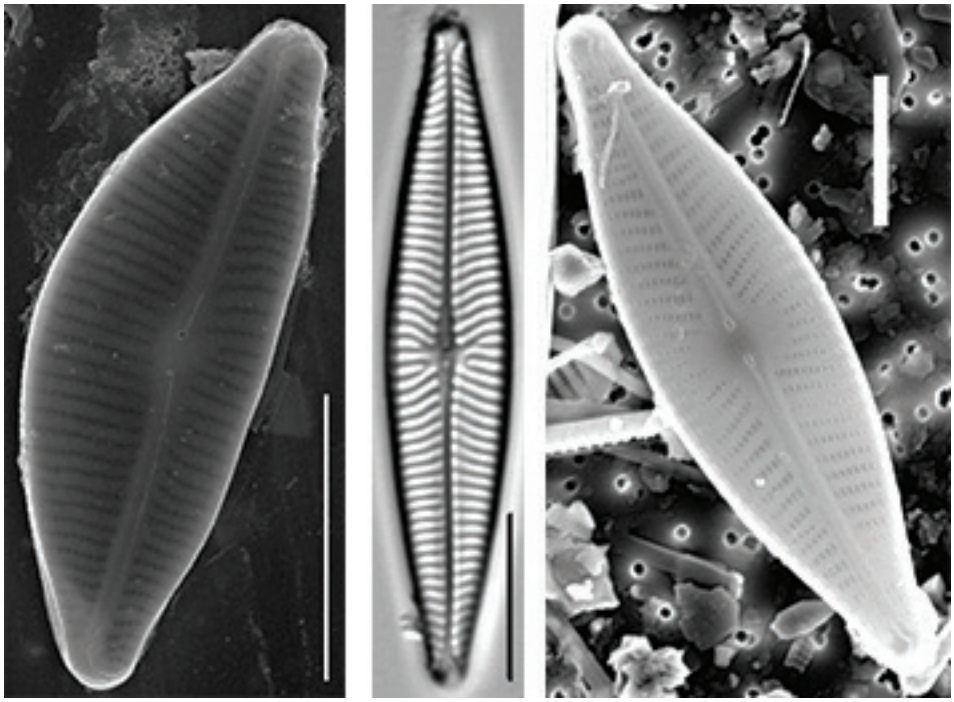


Figure 82. Example light and scanning electron microscope image of new to science diatoms (from left to right): *Encyonema hamsherae, Navicula schweigeri, Navicula caroliniae*. Photos courtesy L. Bahls and P. Kociolek

Table 30. New to science diatoms described from streams in and around Glacier National Park, 2007–2009.

Species	Reference	In the Stream Ecological Integrity sample	Type locality in Glacier National Park
Cavinula davisiae Bahls	Bahls 2013a	–	–
Craticula johnstoniae Bahls	Bahls 2013a	–	Yes
Craticula sardiniana Bahls	Bahls 2013a	–	Yes
Cymatopleura internationale Bahls	Bahls 2013a	–	Yes
Cymbella cosleyi Bahls	Bahls 2013a	–	Yes
Cymbopleura edlundii Bahls	Bahls 2013a	–	Yes
Encyonema hamsherae Winter & Bahls	Winter and Bahls 2013	Yes	–
Encyonopsis albertana Bahls	Bahls 2013b	–	–
Encyonopsis bobmarshallensis Bahls	Bahls 2013b	–	–
Encyonopsis czarneckii Bahls	Bahls 2013b	–	Yes
Encyonopsis descriptiformis Bahls	Bahls 2013b	–	–
Encyonopsis hustedtii Bahls	Bahls 2013b	–	Yes
Encyonopsis medicinalis Bahls	Bahls 2013b	–	Yes
Encyonopsis montana Bahls	Bahls 2013b	–	Yes
Encyonopsis stafsholtii Bahls	Bahls 2013b	–	Yes
Fragilariforma horstii Morales	Morales et al. 2012	Yes	–
Gomphosinica kociolek, You, Wang & Liu	Kociolek et al. 2015	–	–
Gomphosinica capitata Kociolek, You & Wang, sp. nov.	Kociolek et al. 2015	–	Yes
Gomphosinica giacieriana Kociolek, You & Wang, sp. nov.	Kociolek et al. 2015	–	Yes
Gomphosinica robusta Kociolek, You & Wang, sp. nov.	Kociolek et al. 2015	–	Yes
Gomphosinica subtilis Kociolek, You & Wang, sp. nov.	Kociolek et al. 2015	–	Yes
Kurtkrammeria Bahls	Bahls 2015	–	–
Kurtkrammeria lacusglacialis Bahls	Bahls 2015	–	Yes
Kurtkrammeria treinishii Bahls	Bahls 2015	–	–
Navicula caroliniae Bahls	Bahls 2012a	Yes	Yes
Navicula flatheadensis Bahls	Bahls 2012a	–	Yes
Navicula schweigeri Bahls	Bahls 2012a	–	Yes
Navicula trilatera Bahls	Bahls 2013a	–	Yes
Navicula weberi Bahls	Bahls 2012a	–	Yes
Navicula whitefishensis Bahls	Bahls 2012c	–	–
Navicula winona Bahls	Bahls 2012a	–	Yes
Neidium bobmarshallensis Bahls	Bahls 2013b	–	–
Nupela potapovae Bahls	Bahls 2011	–	Yes
Stauroneis akamina Bahls	Bahls 2010	–	Yes
Stauroneis ancepsfallaYes Bahls	Bahls 2010	–	Yes
Stauroneis finlandia Bahls	Bahls 2010	–	Yes
Stauroneis kishinena Bahls	Bahls 2010	–	Yes
Stauroneis kootenai Bahls	Bahls 2010	–	Yes
Stauroneis paYes Bahls	Bahls 2010	–	Yes
Stauroneis pikuni Bahls	Bahls 2010	–	Yes
Stauroneis regina Bahls	Bahls 2010	–	–
Stauroneis reYes Bahls	Bahls 2010	–	–
Stauroneis sacajaweae Bahls	Bahls 2012b	–	–
Stauroneis subborealis Bahls	Bahls 2010	–	–
Stauroneis submarginalis Bahls	Bahls 2010	–	–
Stauroneis superkuelbsii Bahls	Bahls 2010	–	Yes

nated Biphenyls (PCBs) was associated with zebra mussels, indicating that concentration of pollutants in zebra mussel feces can transfer to other trophic levels (Bruner et al. 1994). Zooplankton communities have also been affected by invasions of zebra mussels (MacIsaac and Rocha 1995).

We found no zebra or quagga mussels in our 2007–2009 survey. As reported in Schweiger et al. (in preparation a) we also did not see these species in subsequent annual monitoring at four sentinel sites through 2016.

3.8.4.2 New Zealand mudsnails

New Zealand mudsnails (*Potamopyrgus antipodarum*) are native to New Zealand. They were first discovered in Idaho in 1987. By 1996, they had reached Yellowstone National Park. They are widespread in California, the lower Columbia River, Washington, in the Colorado River basin, including Boulder Creek near Rocky Mountain National Park, and in central Montana north of Helena (Figure 83). Mudsnails tolerate siltation, thrive in disturbed watersheds, and benefit from high nutrient flows. They have the ability to reproduce quickly and mass in high densities and can impact trophic

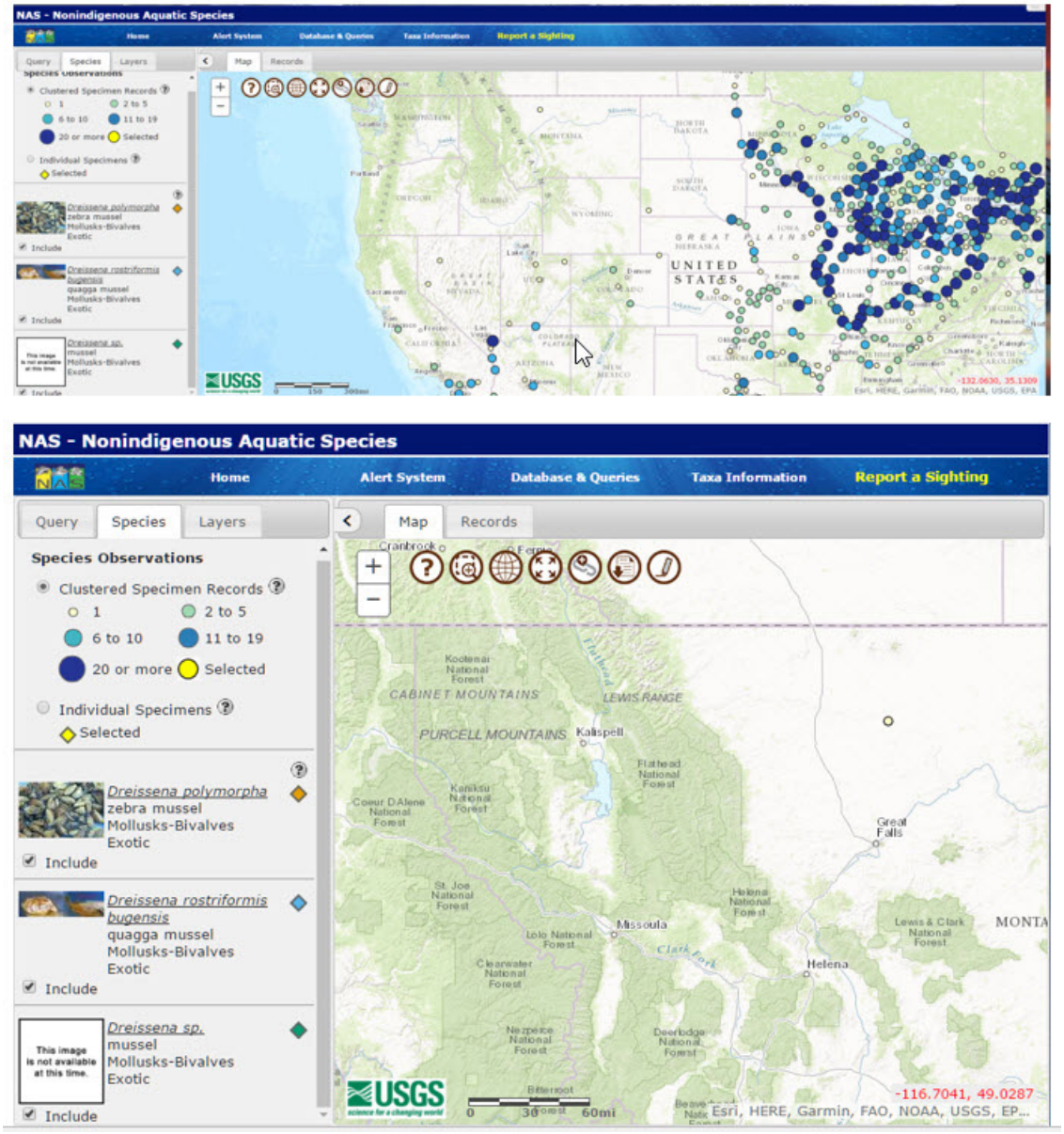


Figure 83. Point locations of the New Zealand mudsnail (*Potamopyrgus antipodarum*) in the Northwest United States (top) and in the Montana/Idaho area (bottom), as of June 2017. Dot size indicates the size of known populations. Data are from several (uncoordinated) sample designs and therefore are not a valid sample of this region as a whole. Data span 1987 to 2017. Data and map courtesy of the USGS Nonindigenous Aquatic Species program.

dynamics of native trout fisheries and alter the physical characteristics of the streams themselves (Benson et al. 2017b). We found no New Zealand mudsnails in our 2007–2009 survey. As reported in Schweiger et al. (in preparation a), we also did not see these species in subsequent annual monitoring at four sentinel sites through 2016.

In general, given the detections of mussels in water samples from Tiber and Canyon Ferry Reservoirs (about 100 miles east of the park) and confirmed New Zealand mudsnail populations in northwest Montana, we will closely watch for these and other invasive species in future monitoring (Figure 84).

3.8.4.3 Rock snot

Didymosphenia geminata (commonly known as rock snot or didymo) is a diatom native to mountain aquatic habitats of North America and Europe (Blanco and Ector 2009; Schweiger et al. 2011). Didymo can form extensive mats (or blooms, Figure 85), which can be several centimeters thick and up to 20 km (12 mi) in length (Blanco and Ector 2009). Larger blooms can inhibit growth of other algal species, change the

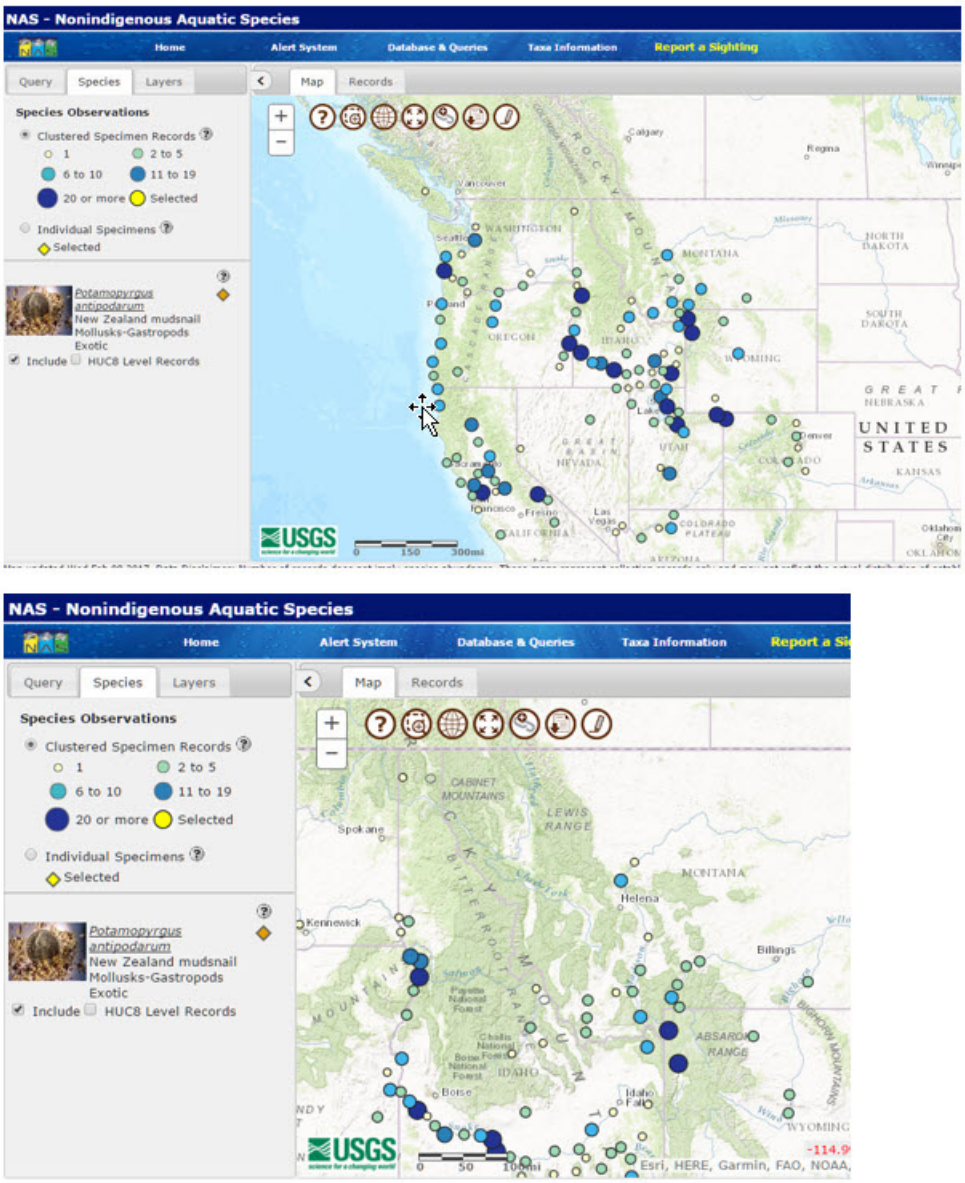


Figure 84. Point locations of zebra and quagga mussel (*Dreissena* spp.) in the Central United States (top) and in the Montana/Idaho area (bottom), as of June 2017. Dot size indicates the size of known populations. Data are from several (uncoordinated) sample designs and therefore are not a valid sample of this region as a whole. Data span 1987 to 2017. Data and map courtesy of the USGS Nonindigenous Aquatic Species program.

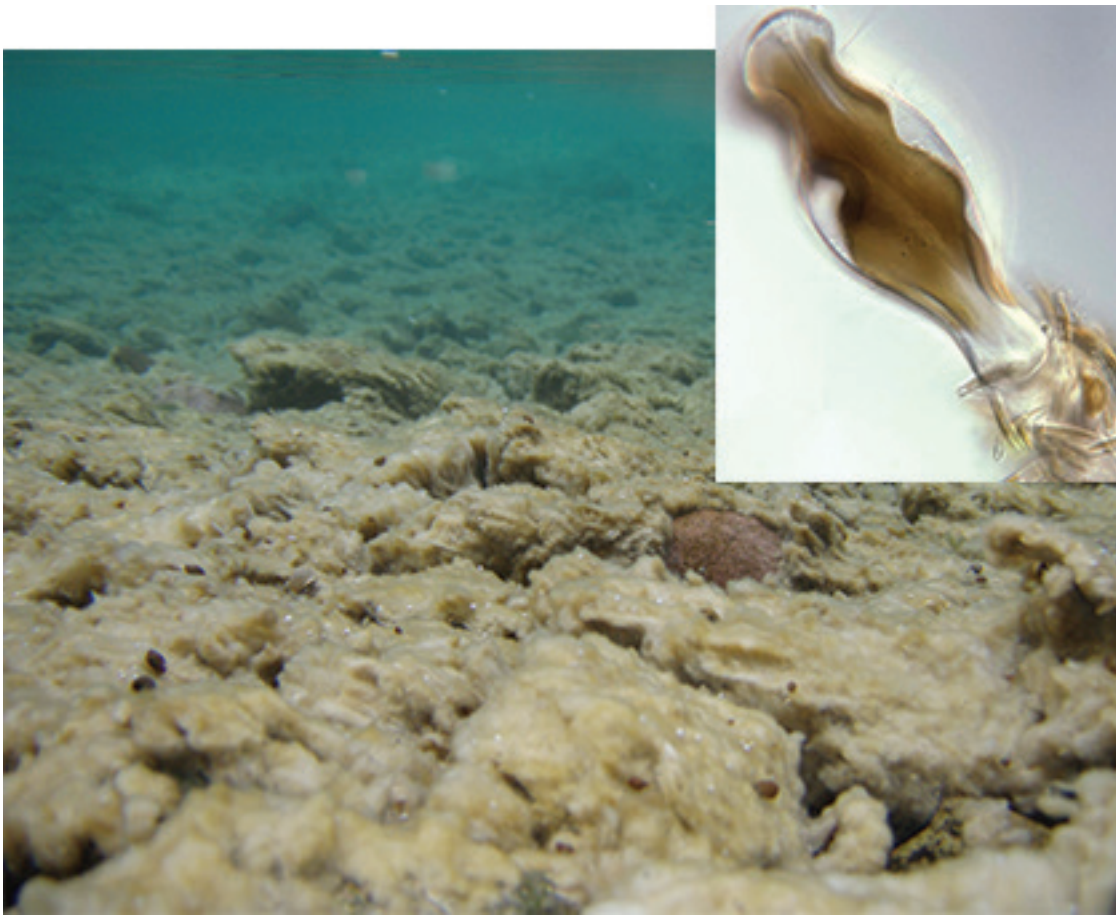


Figure 85. Didymo bloom in McDonald Creek below McDonald Lake in Glacier National Park, 2009. Inset shows light microscope image (at 400 x) of a didymo valve and its stalk. Site photo by NPS/BILLY SCHWEIGER; Inset image by L. BAHLS.

composition of aquatic communities, decrease the amount of suitable spawning habitat for fish, and cause changes in stream chemistry (Spaulding and Elwell 2007). Blooms of didymo also greatly decrease the aesthetic appeal of streams – an important consideration for a tourist destination like Glacier National Park.

In recent years didymo has expanded into lower elevations, latitudes, and new regions of the globe (Kumar et al. 2009). In Montana, didymo was first reported in 1929 at Flathead Lake (Prescott and Dillard 1979) and has likely been present in the northern Rockies since at least the end of the last ice age, about 10,000 years ago (Bahls 2007). Figure 86 shows confirmed point locations (as of 2011) of didymo in the Montana region from work conducted by the EPA and the network. Recent research suggests that didymo is associated with high mean summer temperature, a stable base flow index (less variation in stream flow), and is more abundant in nutrient-poor systems (Kumar et al. 2009).

Results presented in detail in Schweiger et al. (2011) from the 2007–2009 survey showed that didymo was widespread, occurring in 64% of the park's streams. Models suggested that didymo was positively related to summer water temperatures, the proportion of cobble substrate, and Julian date (indicating that didymo abundance increased during our sample period). Conversely, didymo abundance was negatively related to distance from lakes (with higher abundances near lake outlets), total nitrogen concentration, and specific conductance. It was not connected to human use of streams or their riparian corridors.

Of 11 sites revisited in 2007–2009, didymo abundance increased at eight and decreased at only one (Upper Camas Creek; Figure 87). Where we had five or more visits, we found statistically significant increases at three sites. Importantly, however, our period of record is short and the sample size of revisited sites is small. Abundance also varied spatially, with the highest abundances of didymo on the west side of the Continental Divide (Figure 88).

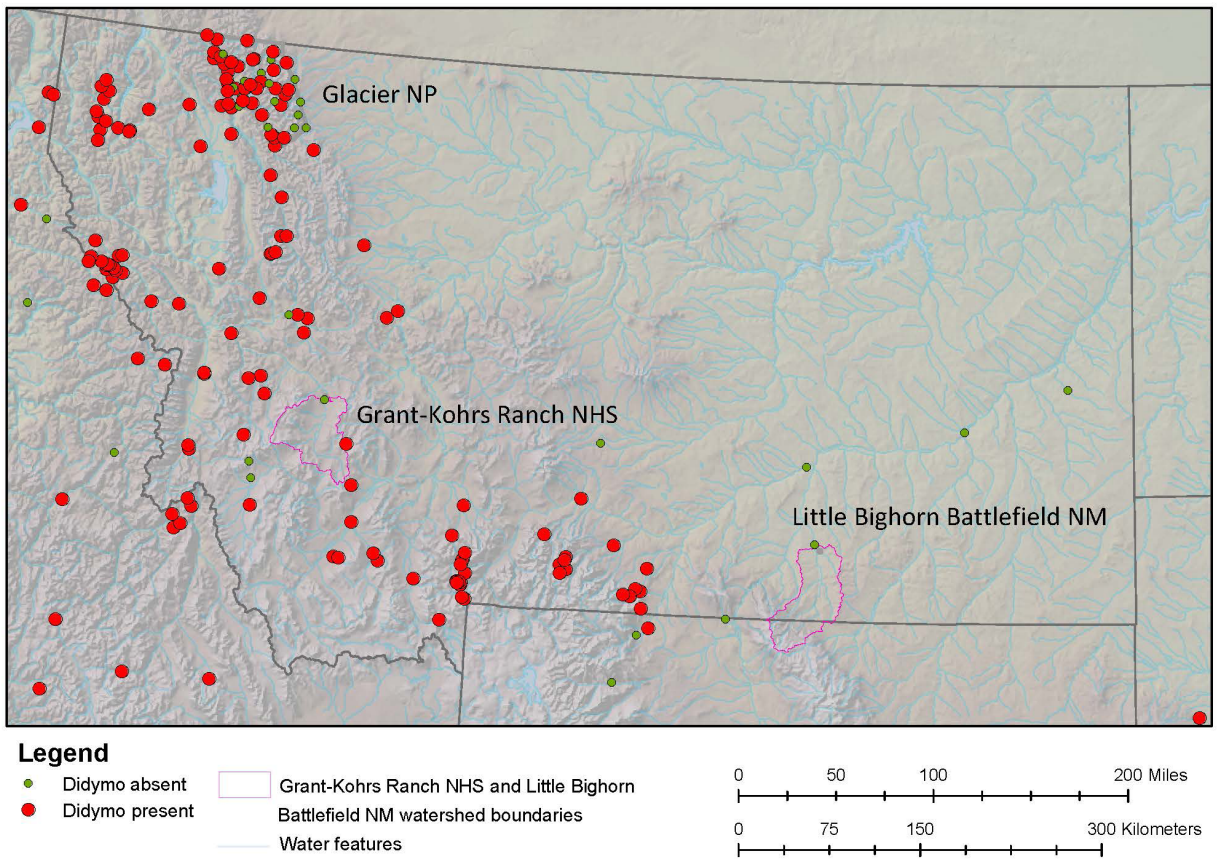


Figure 86. Point locations of confirmed presence of didymo (Didymosphenia geminata) in the Montana region. Data are from several (uncoordinated) sample designs and therefore are not a valid sample of this region as a whole. Data span 2004–2009. Records outside of Glacier National Park are based on data from USGS National Water Quality Assessment (NAWQA), EPA Environmental Monitoring and Assessment (EMAP), and samples from other studies and are courtesy Karl Hermann, Sarah Spaulding, and Tera Keller. Data in Glacier National Park are from the Rocky Mountain Network Stream Ecological Integrity monitoring.

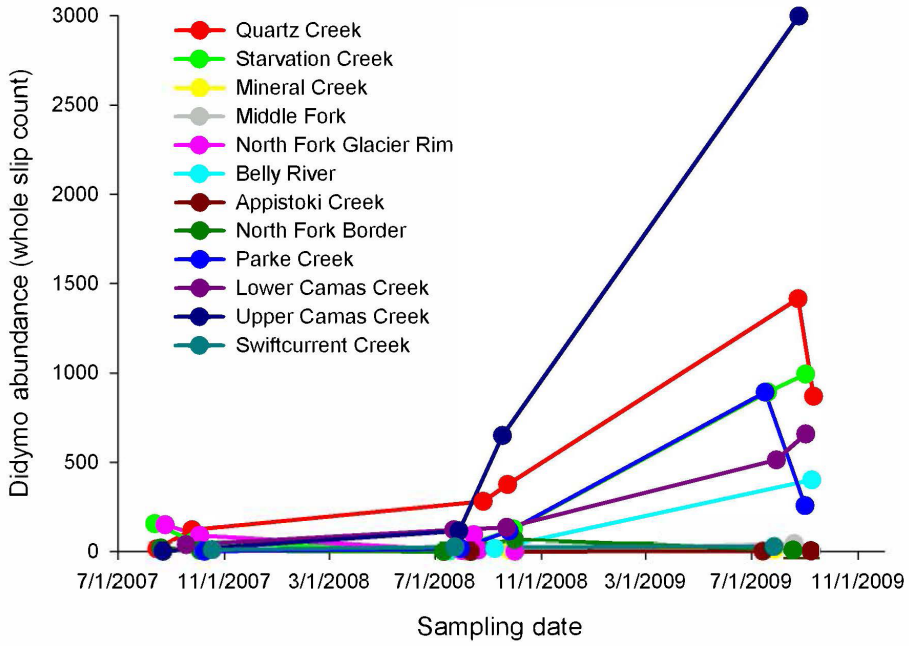


Figure 87. *Didymosphenia geminata* (didymo) abundance from 2007 to 2009 at 11 Glacier National Park stream sites.

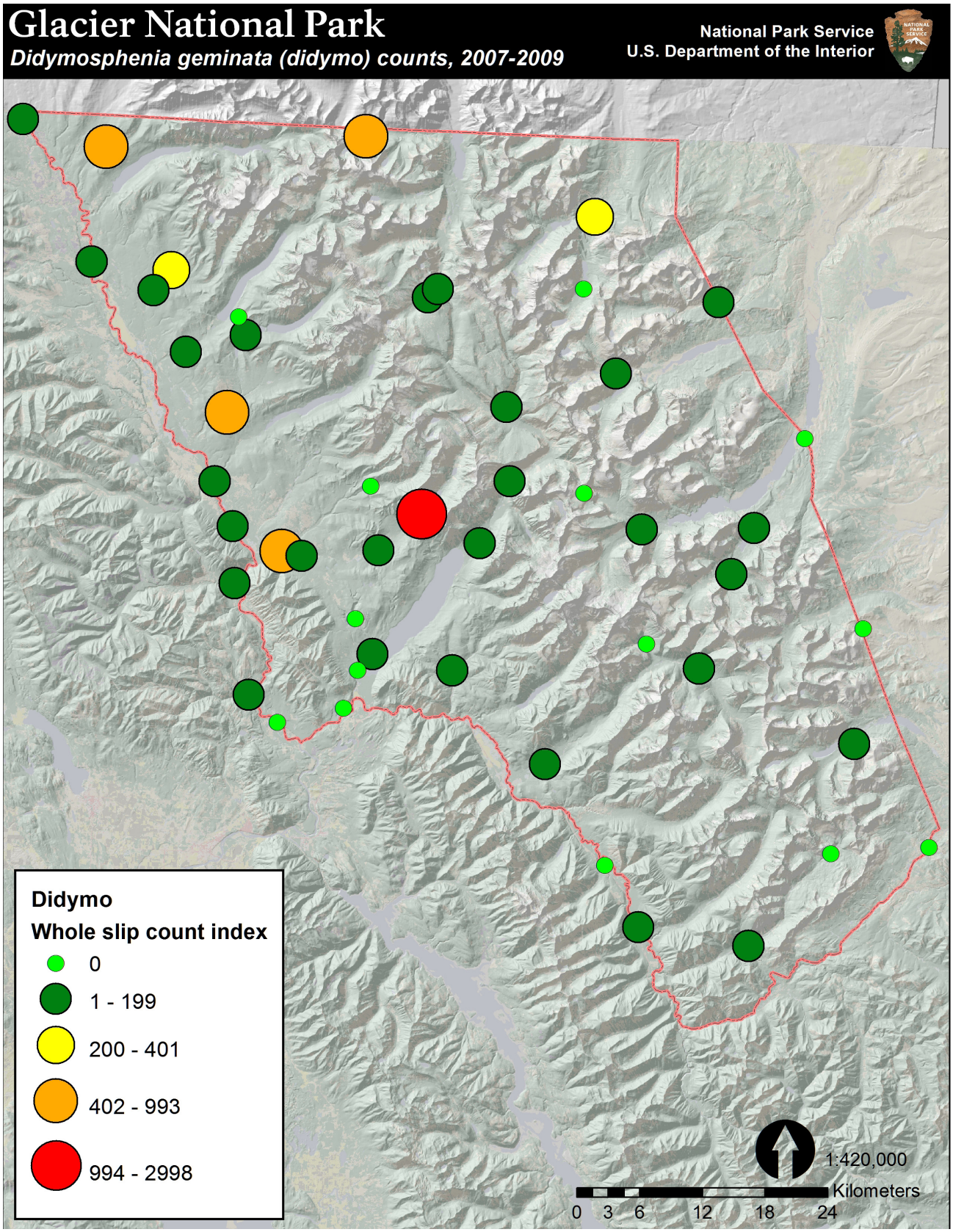


Figure 88. *Didymosphenia geminata* (didymo) abundance index from whole slip counts, Glacier National Park, 2007–2009. Classes are based on a natural breaks algorithm (and thus have no assessment interpretation). Red color and larger circles indicate a higher count index. See Appendix A for a complete list of site numbers and names.

Our results suggest that didymo was widespread and likely became more abundant in Glacier National Park from 2007 to 2009. Our models are generally consistent with other studies of the factors associated with the presence and abundance of didymo (Kumar et al. 2009; Blanco and Ector 2009). Three of the most important and climate change relevant predictors of elevated didymo abundance we found were higher stream temperature, reduced distance from upstream lakes (as a proxy for stable base flows), and lower nitrogen concentration. If current climate trends continue, each of these may change in ways that favor increased didymo abundance and blooms in Glacier National Park. Stream temperatures are expected to rise (Pederson et al. 2010). Lower summer base flows are more likely given the shift towards earlier runoff and higher contribution from surface flow (Hall and Fagre 2003). Finally, as climate change continues to reduce snowpack, groundwater recharge rates will likely decrease and surface water and rainfall may be larger contributors to base flow, both generally having lower nitrogen concentrations (Hauer et al. 2002). Though we cannot make quantitative predictions given the complexity of the response and the state of our current models, our results do suggest that additional research should be conducted to better understand the dynamics of this species, how it may be influenced by climate change, and how it may impact the aquatic ecosystems of Glacier National Park.

4 Management Applications and Future Directions

A fundamental goal of network inventory and long-term monitoring is to provide park managers with data and information useful for protecting and managing park resources. Glacier managers must ultimately decide if and how they will use network stream monitoring data and information. We provide some suggestions for consideration here.

4.1 Background on streams in Glacier National Park and the Crown of the Continent Ecosystem

It is helpful to put the stream ecosystems of Glacier into historical and ecological perspective. Glacier was established in 1910 as the eighth US national park. It is primarily a "headwaters park," as three major river systems originate in the park: the Hudson, the Missouri-Mississippi, and the Columbia. The North Fork of the Flathead River, a Wild and Scenic River (designated in 1976), forms the western boundary of Glacier and originates upstream of the park in British Columbia.

The combination of Glacier and Waterton Lakes National Park in Canada was designated as the world's first International Peace Park in 1932. Together they form the core of the Crown of the Continent Ecosystem (CCE), which, as described by Prato and Fagre (2007), is a "landscape that has escaped the heavy hand of modern humans, a place so vast and undeveloped that much of it is still road less wilderness." Within the CCE, they continue, "whole river systems still function here without the impediment of dams, flowing seaward with glass-clear, unpolluted waters."

4.2 Historical and potential stream issues in Glacier National Park

Before Glacier was established, the area had a long and varied history of human use, especially by indigenous peoples, but also by hunters and trappers, early explorers, and settlers (Figure 89). However, early human use in Glacier did not include broad scale agricultural or other human development, nor did it include resource extraction activities such as large scale mining or logging likely to negatively impact Glacier streams. Most pre-park establishment human activities likely had minimal negative impacts to the condition and health of Glacier streams. One possible exception is the impact of the Great Northern Railway, which runs along the southern boundary of the park over Mariah Pass, along Bear Creek and the middle Fork of the Flathead River. The railway was completed in 1893 and likely affected (and still impacts), to some degree, the hydrology and condition of the streams in the watershed.

Since the park was established, roads and visitation are important developments in the park that likely affect stream conditions. Examples of the construction and use of park roads include the Going to the Sun Road over Logan Pass (completed in 1932), and construction and use of Montana State Highway 2, which parallels the Great Northern Railway route along the southern boundary of Glacier. Visitation effects include the construction and use of visitor facilities in and near the park (e.g., Lake MacDonald Lodge), and visitor use in the front country and backcountry. Importantly, no large hydrologic development projects have been completed entirely in Glacier, though the Sherburne Reservoir does back up into the park. Note that Glacier does border one of the largest concrete arch dams in the United States, the



Figure 89. Members of the Blackfeet tribe near Two Medicine, circa 1914, Glacier National Park. (GLACIER NATIONAL PARK).

Hungry Horse Dam on the South Fork of the Flathead (NPS 2017). Overall the park has a much lower road density than the non-wilderness portions of the surrounding ecoregions. The mean road density in Glacier is about 0.08 km/km^2, compared to a mean value of about 0.72 km/km^2 in the ecoregion as a whole (USGS 2017c).

Activities in watersheds upstream of the park potentially affect the North Fork of the Flathead and nearby aquatic, riparian, and upland ecosystems in Glacier. In the 2000s, there were plans for mining and coal bed methane development in the North Fork of the Flathead drainage, which could potentially affect stream health in the North Fork of the Flathead in Glacier. In February 2010, the Province of British Columbia and the State of Montana signed a Memorandum of Understanding to preclude mining, oil and gas development, and coalbed methane extraction in the Flathead. Under the agreement, mining, oil and gas, coalbed methane, and coal development are prohibited within the basin.

In 2013, the Senate Committee on Energy and Natural Resources considered and passed a bill (S. 255) for federal land in the North Fork of the Flathead drainage "to withdraw certain Federal land and interests in that land from location, entry, and patent under the mining laws and disposition under the mineral and geothermal leasing laws…"

In addition to roads, visitation, and adjacent land use, other kinds of issues may threaten the integrity of Glacier streams. For example, the disappearance of the park's glaciers, declines in winter snowpack, likely rapid climate change-induced increases in the frequency and severity of wildfires, atmospheric deposition of nutrients, invasive species, such as New Zealand mudsnails or quagga mussels (among others), and other issues may impact the park's streams. There are also many potential site (or stream reach) scale problems that might occur (e.g., spills or sediment loading into the Middle Fork of the Flathead from the railroad or highway, or an issue with a visitor facility in the park). This is the primary reason continued monitoring of Glacier stream ecological integrity is important: to help managers understand the status and trend in stream condition and what and how management actions may address these problems.

4.3 Uses of Rocky Mountain Network stream data

We employed several classes of indicators to monitor the status and trend (trend analysis available in Schweiger et al. in preparation a) of stream condition. These included multiple measures of water and sediment quality, physical habitat, and biology (macroinvertebrate and diatom communities). The approach of the stream protocol is to integrate or interpret these measures in concert as indicators of the ecological integrity of the system and to emphasize individual metrics that are likely direct estimators of integrity. We interpret results using a variety of assessment mechanisms, including regulatory criteria (but in a non-regulatory way), other relevant assessment points from the literature, and where possible, reference values derived from state and federal monitoring reference sites in the Middle Rockies Ecoregion. Because SEI monitoring is not regulatory in nature, we consider assessment points that may have more of an ecological basis or are relevant to a specific Glacier resource management need.

Our estimates of stream ecological integrity and our suite of bioassessment models serve as baselines for understanding the current status and future changes/trends in the relatively pristine Glacier stream ecosystems. This provides a useful (and largely heretofore missing) broad scale ecological perspective on streams across the park. In addition, our stream monitoring data provide basic information that can help Glacier management report on and meet basic regulatory requirements (e.g., under the Clean Water Act). This monitoring also provides independent data and estimates of stream and water chemistry data that can be used with partners, such as Montana DEQ and the EPA, to understand and regulate streams in the park if necessary.

4.4 Future stream monitoring in Glacier National Park

This effort has been, and will continue to be, a cooperative undertaking between network staff, partner scientists (for example, scientists with Flathead Lake Biological Station, who we partnered with during protocol development), the USGS West Glacier Field Station staff, and most importantly, Glacier resource managers and biologists. We believe our results, representing the efforts of many dedicated scientists and resource managers over many years, are valid, representative, and useful for understanding and managing streams in the park. As we continue to work with park managers to monitor and understand stream dynamics and ecological integrity in Glacier, we will adapt our approach and methods to park planning and management needs.

5 Glossary

Algae: Aquatic organisms that photosynthesize but lack a vascular system. Some are microscopic, others very large.

Aquatic macroinvertebrate or benthic macroinvertebrate: An organism found in waterbodies, frequently associated with stream bottoms, that does not having a spinal column and is visible with the naked eye.

Ash free dry mass: The weight (mass) of a material obtained by first drying the material at 105 ºC and then heating the material to 500 ºC for 1 hour.

Assessment point: A point along a continuum of indicator values where scientists and managers have together agreed to assess or document the status or trend of a resource relative to program goals, natural variation, or potential concerns. The direction of a condition or disturbance state is indicated by an inequality associated with the assessment point. For example a ">2.0" for a reference state means that values above 2.0 are in reference.

Base flow: The portion of stream flow that comes from groundwater and not runoff.

Baseline: A value or range of values calculated from a time series of data (from one to many years; if many, the time period is often referred to as a "Period of Record"). Baselines may not necessarily be ecological or management assessment points, but could be used in a similar way to assess monitoring data.

Beneficial use: A valuable characteristic of a stream or river resource that, directly or indirectly, contributes to human welfare.

Benthic: On or associated with the sediments or bottom of a body of water.

Bioassessment: Using biological community indicators to assess the health or ecological integrity of an ecosystem.

Biomass: The total mass or amount of living or dead organisms in a particular area or volume.

Chlorophyll-a: The major green pigment found in the chloroplasts of plants and algae.

Criteria: In the context of stream ecological integrity monitoring, an assessment point set by well-established regulatory process; may or may not be ecologically or management relevant for a park resource.

Diatom: Any one of a number of microscopic algae, which can live as single cells or in colonies, that are enclosed within two box-like parts or valves (called frustules) made of silica that fit together like the halves of a Petri dish. When algae are collected from the bottom substrate of streams they may be referred to as periphyton.

Diel: Involving a 24-hour period that usually includes a day and the adjoining night.

Disturbance class: In the context of stream ecological integrity monitoring, disturbance classes are as follows:

> **Negligible**: a negligible impact is barely detectable and/or would result in no measurable or perceptible changes to streams. Negligible impact corresponds to a minimally disturbed condition (MDC) as used in the ecological monitoring literature.
>
> **Minor**: a minor impact is where an impact is slight but detectable and/or would result in small but measurable changes in streams and/or stream hydrology and the effects would be localized. Minor impact corresponds to a least disturbed condition (LDC) as used in the ecological monitoring literature.
>
> **Moderate**: a moderate impact is readily apparent and/or would result in easily detectable changes to streams and/or stream hydrology and the effects would be localized.
>
> **Major**: a major impact is severely adverse and would result in appreciable changes to streams and/or stream hydrology, with the effects often regionally important.

Driver: Environmental factor that influences (or causes a response in) a community or ecosystem. A driver is a natural factor (as opposed to a human or anthropogenic factor) that is within the "natural range of variability."

Ecological integrity: Ecological integrity is the capacity to support and maintain a balanced, integrated, and adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of natural habitats of the region.

Ecological threshold: In general, this is a break point(s) or a "break range" that describes a shift in an ecological response measure and bounds regions in a response's distribution. Thresholds often describe meaningful changes in the ecology of a system. They may involve a nonlinear, rapid, or large response relative to the inputs to a system. They often create a new state from which it is difficult to recover.

Ephemeral stream: A stream or stream segment that flows only in direct response to precipitation in the immediate watershed or in response to the melting of a cover of snow and ice and whose channel bottom is always above the local water table.

Eutrophication: The process of enrichment of a waterbody by nutrients, usually nitrogen- and phosphorus-containing compounds, and the resulting increase in primary productivity (algal and plant growth and decay). Some definitions include organic enrichment of a waterbody as part of eutrophication.

Gradient site: In the context of stream ecological integrity monitoring, a stream site sampled once or multiple times to characterize stream condition under a gradient of (primarily) human disturbance – either under stress or in an unstressed pristine condition.

HDI: Human Disturbance Index – an index of various field and remotely sensed indicators of human caused disturbance, such as agricultural use, roads, trails, etc.

***In-situ* water chemistry**: water chemistry indicator, such as electric conductivity or pH measured in the field.

Intermediate condition: In the context of stream ecological integrity monitoring, an ecological condition between reference and non-reference condition.

Intermittent stream: A stream or stream segment that is below the local water table for at least some part of the year and obtains its flow from both surface runoff and groundwater discharge.

Least Disturbed Condition (LDC): In some (if not many) cases, the lack of availability of a minimally disturbed condition (MDC) or a completely undisturbed reference site makes it necessary to resort to the concept of "least-disturbed condition." Least-disturbed condition is defined as the best available state within a defined region. The LDC may include measurable anthropogenic stress and disturbance. The concept of a LDC implies that there may be an opportunity for management or restoration of sites to an MDC or best attainable state. This may also be possible with an MDC, but in many cases, the set of actions (i.e., reverse climate change) are beyond the scope of management.

Macroinvertebrate: Aquatic invertebrate fauna that can be captured by a 500-µm net or sieve. This includes arthropods (insects, mites, scuds and crayfish), molluscs (snails, limpets, mussels and clams), annelids (segmented worms), nematodes (roundworms), and platyhelminthes (flatworms).

Mainstem: The principal river within a given drainage basin in the case where a number of tributaries discharge into a larger watercourse.

Management-based assessment point: In the context of stream ecological integrity monitoring, an assessment point with explicit management applications or where management-relevant changes in a response occurs. Management assessment points may be the same as ecological assessment points, especially in wilderness parks or when there is little or no information about the management relevance of a response (in these cases we generally refer to an ecological assessment point). They may be set at some estimated distance from an ecological assessment point to serve as a warning ("surveillance assessment point") or to spur management action ("action assessment point").

Metric: Derived forms of an SEI result. For example a characteristic such as the percentage of an assemblage made up by native species of a biological assemblage (e.g., fishes, algae) that changes in some predictable way with increased human influence.

Minimally Disturbed Condition (MDC): A reference condition characterized by the absence of significant human disturbance. In practice, even in wilderness parks, there is usually some background human impact due to diffuse or indirect factors like climate change, nutrient deposition, or residual historical alterations.

Multimetric Index (MMI): An index constructed of multiple indicators selected in a statistical modeling exercise designed to include only the most relevant parsimonious set of contributing indicators to a response variable.

Non-reference condition: In the context of stream ecological integrity monitoring, a "bad" condition: not intact (e.g., missing some ecological component(s)), unhealthy, having low ecological integrity (used in bioassessment or, in rare cases, where there is a clear functional ecological understanding of the relationship between an indicator and a stressor or impact). Primarily influenced by anthropogenic drivers.

Perennial stream: A stream or stream segment that has flowing water year-round, except during extreme drought.

Periphyton: The microscopic flora and fauna that grow at or are associated with the bottom of a body of water and include microscopic algae, bacteria, and fungi.

Phytoplankton: Free living, generally microscopic algae commonly found floating or drifting in waterbodies such as the ocean, lakes, and streams.

Point source: A discernable, confined, and discrete conveyance, including but not limited to any pipe, ditch, channel, tunnel, conduit, well, discrete fissure, container, rolling stock, or vessel or other floating craft, from which pollutants are or may be discharged.

Reference condition: In the context of stream ecological integrity monitoring, a "good" condition: intact, healthy, having high ecological integrity (used in bioassessment or, in rare cases, where there is a clear functional ecological understanding of the relationship between an indicator and a stressor or impact). Primarily influenced by natural drivers. The region of a response distribution on the "good side" of an assessment point (usually ecological). The reference condition is a distribution as it encompasses natural variation in the response. It is somewhat synonymous with a "natural range of variability." Some authors restrict reference condition to describe a biological response, but the network proposes using it more loosely to refer to any type of response measure. Reference conditions are defined relative to a specific response, target population, and spatiotemporal scale (i.e., this is different for a stream response in Glacier National Park than for the Northern Rockies Ecoregion). Based on the dominant landscape condition, reference conditions may reflect various degrees of background disturbance.

Response measures: Stream (or other) indicators that "respond" to natural (e.g., drought) and human (e.g., agricultural development) drivers and stressors. In contrast to a metric, a response measure is not the result of a calculation.

Salmonids: Ray-finned fish, whose members include salmon, trout, chars, freshwater whitefishes, and graylings.

Saturation: A state in which the gas concentration (e.g., oxygen) in a waterbody is in equilibrium with the local partial pressure of that gas in the atmosphere.

Sentinel site: In the context of stream ecological integrity monitoring, a targeted or hand-picked site sampled (usually annually) to help understand stream dynamics or important for management purposes; results cannot be inferred to other streams.

Standards (water quality standards): In a water quality regulatory context, a term applicable to state waters referring collectively to their designated beneficial uses, criteria, and the non-degradation policy, all in Montana law. Numeric water quality standards are quantified expressions of water quality in state law intended to protect a designated beneficial use or uses.

Status: In the context of stream ecological integrity monitoring, status is a "snap shot" evaluation of an indicator over a well-defined and concise range in time.

Strahler Order: A simple hydrology algorithm used to define stream size based on a hierarchy of tributaries. Streams at the top of the watershed are labeled 1. When two order-1 streams join, they create an order-2 stream. When two order-2 streams join, they create an order-3 stream, and so on. If a stream of lower order (e.g., order-2) joins a stream of higher order (e.g., order-3), the order number of the latter does not change.

Stressor: Environmental factor that influences (or causes a response in) a community or ecosystem. A stressor is a human influence or a natural factor that, because of human action, is outside the "natural range of variability."

Survey: Random probabilistic sampling of a resource (i.e. streams) at intervals (e.g., every 10 years) such that results provide inference to the entire resource; applies to "survey sites" sampled in this analysis.

Trend: A non-cyclic, directional change in a response measure that can be with or without pattern.

Wadeable: A stream whose Strahler order is first through (at most) sixth (1:100,000 map scale), and in which most of the wetted channel is wadeable by a person during base flow conditions.

6 Literature Cited

This includes references from the main body of this report and its appendices.

Abell, R. A., D. M. Olson, E. Dinerstein, P. T. Hurley, J. T. Diggs, W. Eichbaum, S. Walters, W. Wettengel, T. Allnutt, C. J. Loucks et al., editors. 2000. Freshwater ecoregions of North America: A conservation assessment. Island Press, Washington, D.C.

Al-Chokhachy, R., B. B. Roper, and E. K. Archer. 2010. Evaluating the status and trends of physical stream habitat in headwater streams within the interior Columbia River and upper Missouri River basins using an index approach. Transactions of the American Fisheries Society 139(4):1041-1059.

Anderson, M. J., K. E. Ellingsen, and B. H. McArdle. 2006. Multivariate dispersion as a measure of beta diversity. Ecology Letters 9:683-693.

Angradi, T. R. 1999. Fine sediment and macroinvertebrate assemblages in Appalachian streams: a field experiment with biomonitoring applications. Journal of the North American Benthological Society 18(1):49-66.

Angradi, T. R., E. W. Schweiger, B. H. Hill, D. W. Bolgrien, J. M. Lazorchak, E. B. Emery, T. M. Jicha, J. A. Thomas, D. J. Klemm, S. Peterson, D. M. Walters, B. R. Johnson, and M. A. Bagley. 2006. Environmental Monitoring and Assessment - Great River Ecosystems Program (EMAP-GRE) Field Operations Manual. EPA/620/R-06/002. USEPA, Duluth, Minnesota.

Appleman, R. A., R. A. Noble, J. L. Sonderegger, J. A. Stanford, B. K. Ellis, and R. Hauer. 1990. Baseline water-quality conditions for the North Fork Flathead River, British Columbia and Montana. Open File Report MBMG–233. Montana Bureau of Mines and Geology, Butte, Montana.

Aroviita, J., H. Mykrä, T. Muotka, and H. Hämäläinen. 2009. Influence of geographical extent on typology- and model-based assessments of taxonomic completeness of river macroinvertebrates. Freshwater Biology 54(8):1774-1787.

Ashton, I. W. 2010. Observed and projected ecological response to climate change in the Rocky Mountains and Upper Columbia Basin: A synthesis of current scientific literature. Natural Resource Report NPS/ ROMN/ NRR—2010/220. National Park Service, Fort Collins, Colorado.

Bahls, L. L. 2004. Northwest diatoms: A photographic catalogue of species in the Montana Diatom Collection, with ecological optima, associates, and distribution records for the nine Northwestern United States. Volume 1. Hannaea, Helena, Montana.

Bahls, L. L. 2007. Diatom indicators of climate change in Glacier National Park. Intermountain Journal of Sciences 13:99-109.

Bahls, L. L. 2009. The diatom flora of Glacier National Park: Some thoughts on taxonomy and ecology. Helena, Montana. Unpublished Report-661250. Available by request to author.

Bahls, L. L. 2010. Northwest diatoms, Volume 4: *Stauroneis* in the Northern Rockies—50 species of *Stauroneis* sensu stricto from western Montana, northern Idaho, northeastern Washington and southwestern Alberta, including 16 species described as new. Montana Diatom Collection, Helena, Montana.

Bahls, L. L. 2011. *Nupela potapovae* sp. nov. (Bacillariophyta), a lentic alpine species from North America. Diatom Research 26(2):167-174.

Bahls, L. L. 2012a. Seven new species in *Navicula* sensu stricto from the Northern Great Plains and Northern Rocky Mountains. Pp. 19-38 in A. Witkowski, P. Kociolek and P. Compere (eds.), Lange-Bertalot Festschrift: Dedicated to Prof. Dr. Horst Lange-Bertalot on the occasion of his 75th Birthday. Nova Hedwigia Beiheft, Schweizerbart, Stuttgart 141.

Bahls L. L. 2012b. Five new species of *Stauroneis* (Bacillariophyta, Stauroneidaceae) from the northern Rocky Mountains, USA. Phytotaxa 67:1-8.

Bahls, L. L. 2012c. *Navicula whitefishensis*, a new diatom (Bacillariophyta) from the Northern Rockies. Intermountain Journal of Sciences 18, No. 1-4.

Bahls, L. L., 2013a. Northwest diatoms, Volume 5: *Encyonopsis* from western North America: 31 species from Alberta, Idaho, Montana, Oregon, South Dakota, and Washington, including 17 species described as new. Northwest Diatoms Volume 5. ISBN 0945345852, ISBN 978-0-945345-85-5.

Bahls, L. L. 2013b. New diatoms (Bacillariophyta) from western North America. Phytotaxa 82(1):7-28.

Bahls, L. L. 2015. *Kurtkrammeria*, a new genus of freshwater

diatoms (Bacillariophyta, Cymbellaceae) separated from *Encyonopsis*. Nova Hedwigia, 101(1-2):165-190.

Bahls, L. L., M. Teply, R. Sada de Suplee, and M. W. Suplee. 2008. Diatom biocriteria development and water quality assessment in Montana: a brief history and status report. Diatom Research 23(2):533-540.

Bailey, R. C., R. H. Norris, and T. B. Reynoldson. 2004. Bioassessment of freshwater ecosystems using the reference condition approach. Kluwer Academic Publishers, New York.

Baker, D. B., R. P. Richards, T. T. Loftus, and J. W. Kramer. 2004. A new flashiness index: Characteristics and applications to midwestern rivers and streams. Journal of the American Water Resources Association 95:503-522.

Barbour, M. T., J. Gerritsen, B. D. Snyder, and J. B. Stribling. 1999. Rapid bioassessment protocols for use in streams and wadeable rivers: periphyton, benthic macroinvertebrates, and fish. U.S. Environmental Protection Agency, Office of Water, Washington, D.C.

Barbour, M. T., W. F. Swietlik, S. K. Jackson, D. L. Courtemanch, S. P. Davies, and C. O. Yoder. 2000. Measuring the attainment of biological integrity in the USA: A critical element of ecological integrity. Hydrobiologia 422:453-464.

Barnett, T. P., D. W. Pierce, H. G. Hidalgo, C. Bonfils, B. D. Santer, T. Das, G. Bala, A. W. Wood, T. Nozawa, A. A. Mirin, D. R. Cayan, and M. D. Dettinger. 2008. Human-induced changes in the hydrology of the western United States. Science 319:1080-1083.

Bennetts, R. E., J. E. Gross, K. Cahill, C. McIntyre, B. B. Bingham, A. Hubbard, L. Cameron, and S. L. Carter. 2007. Linking monitoring to management and planning: Assessment points as a generalized approach. The George Wright Forum 24:59-77.

Benson, A. J., D. Raikow, J. Larson, A. Fusaro, and A. K. Bogdanoff. 2017a. USGS Quagga mussel fact sheet. USGS Nonindigenous Aquatic Species online Database. https://nas.er.usgs.gov/queries/FactSheet.aspx?SpeciesID=95, accessed June 2017.

Benson, A. J., D. Raikow, J. Larson, A. Fusaro, and A. K. Bogdanoff. 2017b. USGS New Zealand mudsnail fact sheet. USGS Nonindigenous Aquatic Species online database. https://nas.er.usgs.gov/queries/FactSheet.aspx?SpeciesID=1008, accessed June 2017.

Benson, B. J. and J. J. Magnuson. 1992. Spatial heterogeneity of littoral fish assemblages in lakes: relation to species diversity and habitat structure. Canadian Journal of Fisheries and Aquatic Sciences 49:1493-1500.

Biggs, T. W., T. Dunne, and L. A. Martinelli. 2004. Natural controls and human impacts on stream nutrient concentrations in a deforested region of the Brazilian Amazon basin. Biogeochemistry 68:227–257.

Black, J. H., and R. Timken. 1976. Endangered and threatened amphibians and reptiles in Montana. Pp. 36-37 in R. E. Ashton, Jr. (chair), Endangered and threatened amphibians and reptiles in the United States. Society for the Study of Amphibians and Reptiles Herpetological Circular 5:1-65.

Blanco, S., and L. Ector. 2009. Distribution, ecology and nuisance effects of the freshwater invasive diatom *Didymosphenia geminata* (Lyngbye) M. Schmidt: A literature review. Nova Hedwigia 88:347-422.

Blasius, B. J., and R. W. Merritt. 2002. Field and laboratory investigations on the effects of road salt (NaCl) on stream macroinvertebrate communities. Environmental Pollution 120(2):219-231.

Blocksom, K. A. 2003. A performance comparison of metric scoring methods for a multimetric index for Mid-Atlantic Highlands streams. Environmental Management 31:670-682.

Bollman, W. 2006. Summary of aquatic invertebrate data from the Montana statewide monitoring network, 2001-2005. Rhithron Associates, Inc. Missoula, Montana.

Bonada, N., N. Prat, V. H. Resh, and B. Statzner. 2006. Developments in aquatic insect biomonitoring: a comparative analysis of recent approaches. Annual Review of Entomology. doi:10.1146/annurev.ento.51.110104.151124.

Bothwell, M. L., B. W. Taylor, and C. Kilroy. 2014. The Didymo story: the role of low dissolved phosphorus in the formation of *Didymosphenia geminata* blooms. Diatom Research 29(3):229-236.

Brandt, D. 2001. Temperature preferences and tolerances for 137 common Idaho macroinvertebrate taxa. Report to the Idaho Department of Environmental Quality, Coeur d' Alene, Idaho.

Bray, J. R., and J. T. Curtis. 1957. An ordination of upland

forest communities of southern Wisconsin. Ecological Monographs 27:325-349.

Breheny, P., and W. Burchett. 2013. Visualization of regression models using visreg. R Package:1-15.

British Columbia Ministry of the Environment. 1978. Kootenay air and water quality study phase II: Water Investigations Branch.

Britten, M., E. W. Schweiger, B. Frakes, D. Manier, and D. Pillmore. 2007. Rocky Mountain Network vital signs monitoring plan. Natural Resource Report NPS/ ROMN/ NRR-2007/010.

Brookes, A. 1986. Response of aquatic vegetation to sedimentation downstream from river channelisation works in England and Wales. Biological Conservation 38:352-353.

Brown, C. J. D. 1971. Fishes of Montana. Big Sky Books, Montana State University.

Brown, R. L., and R. K. Peet. 2003. Diversity and invasibility of southern Appalachian plant communities. Ecology 84:32-39.

Bruner, K. A., S. W. Fisher, and P. F. Landrum. 1994. The role of the zebra mussel, *Dreissena polymorpha*, in contaminant cycling: II. Zebra mussel contaminant accumulation from algae and suspended particles, and transfer to the benthic invertebrate, *Gammarus fasciatus*. Journal of Great Lakes Research 20:735-750.

Bryce, S. A., G. A. Lomnicky, and P. R. Kaufmann. 2010. Protecting sediment-sensitive aquatic species in mountain streams through the application of biologically-based streambed sediment criteria. Journal of the North American Benthological Society 29(2):657-672.

Buchholtz, C. W. 1976. Man in Glacier. Glacier Natural History Association, Inc., West Glacier, Montana.

Cantilli, R., R. Stevens, W. Swietlik, W. Berry, P. Kaufmann, J. Paul, R. Spehar, s. Cormier, and D. Norton. 2006. Framework for developing suspended and beddedsediments (SABS) water quality criteria. EPA-822-R-06-001. U.S. Environmental Protection Agency, Office of Water, Washington, D.C.

Cao, Y., and C. P. Hawkins. 2011. The comparability of bioassessments: A review of conceptual and methodological issues. Journal of the North American Benthological Society 30:680-701.

Cao, Y., and D. D. Williams. 1999. Rare species are important in bioassessment (Reply to the comment by Marchant). Limnology and Oceanography 44:1841-1842.

Cao, Y., D. D. Williams, and N. E. Williams. 1998. How important are rare species in community ecology and bioassessment. Limnology and Oceanography 43:1043-1049.

Cembella, A. D., N. J. Antia, and P. J. Harrison. 1982. The utilization of inorganic and organic phosphorous compounds as nutrients by eukaryotic microalgae: A multidisciplinary perspective: Part I. CRC Critical Reviews in Microbiology 10(4):317-391.

Chaffin, J. D., S. Mishra, R. M. Kuhaneck, S. A. Heckathorn, and T. B. Bridgeman. 2012. Environmental controls on growth and lipid content for the freshwater diatom, *Fragilaria capucina*: a candidate for biofuel production. Journal of Applied Phycology 24(5):1045-1051.

Chambers, J. M. 1992. Linear models. Chapter 4, in (eds) J. M. Chambers and T. J. Hastie, Statistical Models in S. Wadsworth and Brooks/Cole, Pacific Grove, California.

Chang, F. H., J. E. Lawrence, B. Rios-Touma, and V. H. Resh. 2014. Tolerance values of benthic macroinvertebrates for stream biomonitoring: assessment of assumptions underlying scoring systems worldwide. Environmental Monitoring and Assessment 186(4):2135-2149.

Clarke, R. T., and J. F. Murphy. 2006. Effects of locally rare taxa on the precision and sensitivity of RIVPACS bioassessment of freshwaters. Freshwater Biology 51:1924-1940.

Clews, E., and S. J. Ormerod. 2008. Improving bio-diagnostic monitoring using simple combinations of standard biotic indices. River Research and Applications 25:348-361.

Colwell, R., S. Avery, J. Berger, G. E. Davis, H. Hamilton, T. Lovejoy, S. Malcolm, A. McMullen, M. Novacek, R. J. Roberts, and R. Tapia. 2012. Revisiting Leopold: resource stewardship in the national parks. Published Report-2191510. National Park System Advisory Board Science Committee, Washington, D.C.

Confederated Salish and Kootenai Tribes and Montana Fish, Wildlife & Parks. 2004. Flathead Subbasin plan: Executive summary. A report prepared for the Northwest Power and Conservation Council, Portland,

Oregon.

Crumpton, W. G. 1989. Algae in northern prairie wetlands. Pp. 188–203 in A. van der Valk (ed.), Northern prairie wetlands. Iowa State University Press, Ames.

Crunkilton, R. L., and R. M. Duchrow. 1991. Use of stream order and biological indices to assess water quality in the Osage and Black river basins of Missouri. Hydrobiologia 224(3):155-166.

Dalby, C. 1983. Evaluation and monitoring of the hydrologic impact of Cabin Creek, B.C. coal pit mining on the North Fork of the Flathead River. Technical completion report PB–83–221788. Montana State University, Water Resources Research Center, Bozeman.

Daly, C., M. Halbleib, J. I. Smith, W. P. Gibson, M. K. Doggett, G. H. Taylor, J. Curtis, and P. P. Pasteris. 2008. Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. International Journal of Climatology 28:2031.

Davey, C. A., K. T. Redmond, and D. B. Simeral. 2007. Weather and climate inventory, National Park Service, Rocky Mountain Network. Natural Resource Technical Report NPS/ROMN/NRTR—2007/036, National Park Service, Fort Collins, Colorado.

Davies, S. P., and S. K. Jackson. 2006. The biological condition gradient: a descriptive model for interpreting change in aquatic ecosystems. Ecological Applications 16:1251-1266.

De'ath, G. 1999. Extended dissimilarity: a method of robust estimation of ecological distances from high beta diversity data. Plant Ecology 144:191-199.

Dettinger, M., K. Redmond, and D. Cayan. 2004. Winter orographic precipitation ratios in the Sierra Nevada - large-scale atmospheric circulations and hydrologic consequences. Journal of Hydrometeorology 5:1102-1116.

Diaz-Ramos, S., D. L. Stevens Jr, and A. R. Olsen. 1996. EMAP statistical methods manual. Report nr EPA/620/R-96/002. U.S. Environmental Protection Agency, Office of Research and Development, NHEERL-Western Ecology Division, Corvallis, Oregon.

Dietrich, W. E., J. W. Kirchner, H. Ikeda, and F. Iseya. 1989. Sediment supply and the development of the coarse surface layer in gravel bed rivers. Nature 340(20):215-217.

Diplas, P., P. Chatanantavet, and J. Almedeij. 2016. Streambed structure, stream power, and bed load transport: A unified outlook for gravel-bed and bedrock streams. Pp. 987-993 in River flow 2016. CRC Press, Taylor and Francis Group, Boca Raton, Florida.

Downs, C. C., C. Stafford, H. Langner, and C. C. Muhlfeld. 2011. Glacier National Park fisheries inventory and monitoring bi-annual report, 2009-2010. National Park Service, Glacier National Park, West Glacier, Montana.

Dubrovsky, N. M., K. R. Burow, G. M. Clark, J. M. Gronberg, P. A. Hamilton, K. J. Hitt, D. K. Mueller, M. D. Munn, B. T. Nolan, L. J. Puckett, M. G. Rupert, T. M. Short, N. E. Spahr, L. A. Sprague, and W. G. Wilber. 2010. The quality of our Nation's waters—Nutrients in the Nation's streams and groundwater, 1992–2004. U.S. Geological Survey Circular 1350.

Dudley, T. L., S. D. Cooper, and N. Hemphill. 1986. Effects of macroalgae on a stream invertebrate community. Journal of the North American Benthological Society 5(2):93-106.

Eaton, B., and J. Rosenfeld. 2016. Mechanisms of flow and sediment transport in fluvial ecosystems: Physical and ecological consequences. Chapter 10 (pp.347-382) in A biogeoscience approach to ecosystems. Cambridge University Press, Cambridge, United Kingdom.

Ebert, D. W., and T. G. Wade. 2000. Analytical tools interface for landscape assessments (ATILA) user guide: Version 2.0. U.S. Environmental Protection Agency, Office of Research and Development, Las Vegas, Nevada.

Ellis, B. K., J. A. Craft, and J. A. Stanford. 2015. Long-term atmospheric deposition of nitrogen, phosphorus and sulfate in a large oligotrophic lake. PeerJ 3:e841.

Ellis, B. K., J. A. Stanford, J. A. Craft, D. W. Chess, G. R. Gregory, and L. F. Marnell. 1992. Monitoring water quality of selected lakes in Glacier National Park, Montana: Analysis of data collected, 1984–1990. FLBS Report No. 129-92 in Conformance with Cooperative Agreement CA 1268-0-9001, Work Order 6. National Park Service, Glacier National Park, West Glacier, Montana and Flathead Lake Biological Station, The University of Montana, Polson.

Elser, J. J., M. E. Bracken, E. E. Cleland, D. S. Gruner, W. S. Harpole, H. Hillebrand, J. T. Ngai, E. W. Seabloom, J. B. Shurin, and J. E. Smith. 2007. Global analysis

of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. Ecology letters 10(12):1135-1142.

Fancy S. G., J. E. Gross, and S. L.Carter. 2009. Monitoring the condition of natural resources in US national parks. Environmental Monitoring and Assessment 151(May):161-174.

Fausch, K. D., and T. G. Northcote. 1992. Large woody debris and salmonid habitat in a small coastal British Columbia stream. Canadian Journal of Fisheries and Aquatic Sciences 49(4):682-693.

Feldman, D., and B. Jessup. 2012. An overview of the development process for the Montana coldwater observed/expected model for macroinvertebrate assessments. Draft. WQPBWQSTR-003. Montana Department of Environmental Quality, Helena.

Field, C. B., L. D. Mortsch, M. Brklacich, D. L. Forbes, P. Kovacs, J. A. Patz, S. W. Running, and M. J. Scott. 2007. North America climate change 2007: Impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the Intergovernmental Panel on Climate Change. Pages 617-652 in M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson, editors. Climate Change 2007: Impacts, adaptation and vulnerability. Cambridge University Press, Cambridge, United Kingdom.

Fitzpatrick, F. A., I. R. Waite, P. J. D'Arconte, M. R. Meador, M. A. Maupin, and M. E. Gurtz. 1998. Revised methods for characterizing stream habitat in the National Water-Quality Assessment Program. U.S. Geological Survey Water-Resources Investigations Report 98-4052.

Flathead River North Fork, Study Board. 1988. Report of the Flathead River North Fork, Study Board to the North Fork, Joint Commission. Washington, D.C.

Ford, J. 1989. The effects of chemical stress on aquatic species composition and community structure. Pp. 99-144 in S. A. Levin, M. A. Harwell, J. R. Kelly, and K. D. Kimball (editors). Ecotoxicology: problems and approaches. Springer-Verlag, New York.

Fore, L. S., J. R. Karr, and R. W. Wisseman. 1996. Assessing invertebrate responses to human activities: evaluating alternative approaches. Journal of the North American Benthological Society 15(2):212-231.

Forman, R. T, and L. E. Alexander. 1998. Roads and their major ecological effects. Annual Review of Ecology and Systematics 29:207-231+C2.

Fountain, A. G., M. Hoffman, K. Jackson, H. Basagic, T. Nylen, and D. Percy. 2006. Digital outlines and topography of the glaciers of the American West. USGS Report 1340.

Fraley, J. J., and B. B. Shepard. 1989. Life history, ecology, and population status of migratory bull trout (*Salvelinus confluentus*) in the Flathead Lake and river system, Montana. Northwest Science 63:133-143.

Freeman, M. C., C. M. Pringle, and C. R. Jackson. 2007. Hydrologic connectivity and the contribution of stream headwaters to ecological integrity at regional scales. Journal of the American Water Resources Association. doi: 10.1111/j.1752-1688.2007.00002.x

Friberg, N. 2010. Pressure-response relationships in stream ecology: introduction and synthesis. In: Friberg, N. (ed.) Special issue: pressure-response relationships in stream ecology. Freshwater Biology 55:1367-1381.

Fry, J., G. Xian, S. Jin, J. Dewitz, C. Homer, L. Yang, C. Barnes, N. Herold, and J. Wickham. 2011. Completion of the 2006 National Land Cover Database for the Conterminous United States. Photogrammetric Engineering and Remote Sensing 77(9):858-864.

Giersch, J. J., S. Hotaling, R. P. Kovach, L. A. Jones, and C. C. Muhlfeld. 2016. Climate- induced glacier and snow loss imperils alpine stream insects. Global change biology. doi: 10.1111/gcb.13565

Gildea, J., T. Laidlaw, D. Pridmore, and Steg, R. 2004 Water quality assessment and TMDLs for the Flathead River Headwaters Planning Area, Montana. Prepared by the U.S. Environmental Protection Agency, Montana Operations Office, Flathead National Forest, and Tetra Tech, Inc., for the Montana Department of Environmental Quality.

Goldman, J. C., D. B. Porcella, J. E. Middlebrooks, and D. F. Toerien. 1971. The effect of carbon on algal growth–its relationship to eutrophication. Utah Water Research Laboratory Reports, Paper 462. http://digitalcommons.usu.edu/water_rep/462

Goode, J. R., C. H. Luce, and J. M. Buffington. 2012: Enhanced sediment delivery in a changing climate in semi-arid mountain basins: Implications for water resource management and aquatic habitat in the northern Rocky Mountains. Geomorphology

139-140:1-15.

Gorman, O. T., and J. R. Karr. 1978. Habitat structure and stream fish communities. Ecology 59:507-515.

Green, M. B., and D. Wang. 2008. Watershed flow paths and stream water nitrogen-to-phosphorus ratios under imulated precipitation regimes. Water Resources Research 44(12).

Gregory, S. V, F. J. Swanson, W. A. Mckee, and K. W. Cummins. 1991. An ecosystem perspective of riparian zones. BioScience 41:540-551.

Griffith, M. B., B. H. Hill, F. H. McCormick, P. R. Kaufmann, A. T. Herlihy, and A. R. Selle. 2005. Comparative application of indices of biotic integrity based on periphyton, macroinvertebrates, and fish to southern Rocky Mountain streams. Ecological Indicators 5(2):117-136.

Grömping, U. 2006. Relative importance for linear regression in R: The Package relaimpo. Journal of Statistical Software 17, Issue 1. http://www.jstatsoft.org/v17/i01 (accessed September 2017)

Gurnell, A. M. 1998. The hydrogeomorphological effects of beaver dam-building activity. Progress in Physical Geography 22(2):167-189.

Gurnell, A. M., H. Piegay, F. J. Swanson, and S. V. Gregory. 2002. Large wood and fluvial processes. Freshwater Biology 47(4):601-619.

Hall, M. H. P., and D. B. Fagre. 2003. Modeled climate-induced glacier change in Glacier National Park, 1850–2100. Bioscience 53(2):131-140.

Hamilton, A. T., J. D. Stamp, and B. G. Bierwagen. 2010. Vulnerability of biological metrics and multimetric indices to effects of climate change. Journal of the North American Benthological Society 29(4):1379-1396.

Hankin, D. G., and G. H. Reeves. 1988. Estimating total fish abundance and total habitat area in small streams based on visual estimation methods. Canadian Journal of Fisheries and Aquatic Sciences 45:834-844.

Hansen, A. J., N. Piekielek, C. Davis, J. Haas, D. M. Theobald, J. E. Gross, W. B. Monahan, T. Olliff, and S. W. Running. 2014. Exposure of US National Parks to land use and climate change 1900–2100. Ecological Applications 24(3):484-502.

Hanzel, D. A. 1959. The distribution of the cutthroat trout (*Salmo clarki*) in Montana. Proceedings of the Montana Academy of Sciences 19: 32-71.

Harmon, M. E., J. F. Franklin, F. J. Swanson, P. Sollins, S. V. Gregory, J. D. Lattin, N. H. Anderson, S. P. Cline, N. G. Aumen, J. R. Sedell, G. W. Lienkaemper, K. Cromack Jr., and K. W. Cummins. 1986. Ecology of coarse woody debris in temperate ecosystems. Advances in Ecological Research 15:133-302.

Harper, D. D., and A. M. Farag. 2004. Winter habitat use by cutthroat trout in the Snake River near Jackson, Wyoming. Transactions of the American Fisheries Society 133:15-25.

Hartwig, M., M. Schäffer, P. Theuring, S. Avlyush, M. Rode, and D. Borchardt. 2016. Cause–effect–response chains linking source identification of eroded sediments, loss of aquatic ecosystem integrity and management options in a steppe river catchment (Kharaa, Mongolia). Environmental Earth Sciences 75(10):1-13.

Hauer, F. R., J. S. Baron, D. H. Campbell, K. D. Fausch, S. W. Hostetler, G. H. Leavesley, P. R. Leavitt, D. M. McKnight, and J. A. Stanford. 1997. Assessment of climate change and freshwater ecosystems of the Rocky Mountains, USA and Canada. Hydrological Processes 11:903-924.

Hauer, F. R., D. B. Fagre, and J. A. Stanford. 2002. Hydrologic processes and nutrient dynamics in a pristine mountain catchment. Verhandlungen des Internationalen Verein Limnologie 28:1490-1493.

Hauer, F. R., H. Locke, V. J. Dreitz, M. Hebblewhite, W. H. Lowe, C. C. Muhlfeld,. C. R. Nelson, M. F. Proctor, and S. B. Rood. 2016. Gravel-bed river floodplains are the ecological nexus of glaciated mountain landscapes. Science Advances 2(6):p.e1600026.

Hauer, F. R., J. A. Stanford, J. Giersch, and W. H. Lowe. 2000. Distribution and abundance patterns of macroinvertebrates in a mountain stream: an analysis along multiple environmental gradients. Verh Internat Verein Limnol 27:1-4.

Hauer, F. R., J. A. Stanford, and M. S. Lorang. 2007. Pattern and process in northern Rocky Mountain headwaters: Ecological linkages in the headwaters of the Crown of the Continent. Journal of the American Water Resources Association 43:104-117.

Hawkins, C. P. 2005. Development of a RIVPACS (O/E)

model for assessing the biological integrity of Montana streams. Utah State University, The Western Center for Monitoring and Assessment of Freshwater Ecosystems, Logan.

Hawkins, C. P., M. L. Murphy, and N. J. Anderson. 1983. Density of fish and salamanders in relation to riparian canopy and physical habitat in streams of the northwestern United States. Canadian Journal of Fisheries and Aquatic Sciences. 40(8):1173-1186.

Hawkins, C. P., R. H. Norris, J. N. Hogue, and J. W. Feminella. 2000. Development and evaluation of predictive models for measuring the biological integrity of streams. Ecological Applications 10:1456-1477.

Hawkins, C. P., J. Ostermiller, M. Vinson, R. J. Stevenson, and J. Olsen. 2003. Stream algae, invertebrate, and environmental sampling associated with biological water quality assessments: filed protocols. Utah State University, Logan.

Heard, A. M. 2005. Effects of landscape scale prescribed fire on hydrology and stream chemistry. Colorado State University, Fort Collins.

Heitke, J. D. E. K. Archer, R. J. Leary, and B. B. Roper. 2011. Effectiveness monitoring for streams and riparian areas: sampling protocol for stream channel attributes. https://www.fs.fed.us/biology/resources/pubs/feu/pibo/pibo_2008_stream_sampling_protocol.pdf. (accessed 9/26/2017).

Helsel, D. R. 2005. Nondetects and data analysis: statistics for censored environmental data. Wiley, New York.

Hem, J. D. 1989. Study and interpretation of chemical characteristics of natural water, 3rd edition. United States Geological Survey, Water-Supply Paper 2254.

Hilsenhoff, W. L. 1982. Using a biotic index to evaluate water quality in streams. Pp. 1-22. Department of Natural Resources, Madison, Wisconsin.

Hirsch, R. M., R. B. Alexander, and R. A. Smith. 1991. Selection of methods for the detection and estimation of trends in water quality. Water Resources Research 27(5):803-813.

Hobbs, R. J., and L. F. Huenneke. 1992. Disturbance, diversity, and invasion: implications for conservation. Conservation Biology 6:324-337.

Holland, R. E. 1993. Changes in planktonic diatoms and water transparency in Hatchery Bay, Bass Island Area, Western Lake Erie since the establishment of the zebra mussel. Journal of Great Lakes Research 19:617-624.

Homer, C., J. Dewitz, J. Fry, M. Coan, N. Hossain, C. Larson, N. Herold, A. McKerrow, J. N. VanDriel, and J. Wickham. 2007. Completion of the 2001 National Land Cover Database for the conterminous United States. Photogrammetric Engineering and Remote Sensing 73:337-341.

Homer, C. G., J. A. Dewitz, L.Yang, S. Jin, P. Danielson, G. Xian, J. Coulston, N. D. Herold, J. D. Wickham, and K. Megown. 2015. Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing 81:345-354.

Hop, K., M. Reid, J. Dieck, S. Lubinski, and S. Cooper. 2007. U.S. Geological Survey-National Park Service Vegetation Mapping Program: Waterton-Glacier International Peace Park. U.S. Geological Survey, Upper Midwest Environmental Sciences Center, La Crosse, Wisconsin.

Horowitz, A. J. 2008. Determining annual suspended sediment and sediment-associated trace element and nutrient fluxes. Science of the Total Environment 400:315-343.

Horvitz, D. G., and D. J. Thompson. 1952. A generalization of sampling without replacement from a finite universe. Journal of the American Statistical Association 47:663-685.

Hostetler, S. W., J. R. Alder, and A. M. Allan. 2011. Dynamically downscaled climate simulations over North America: Methods, evaluation and supporting documentation for users. U.S. Geological Survey Open-File Report 2011-1238. http://regclim.coas.oregonstate.edu/index.html

Hubler, S. 2007. Wadeable stream conditions in Oregon. Oregon Department of Environmental Quality Laboratory Division—Watershed Assessment Section Watershed Assessment Section Hillsboro, Oregon U.S.A. DEQ07-LAB-0081-TR.

Hughes, R. M. 1995. Defining acceptable biological status by comparing with reference conditions. Pp. 31-47 in: W. S. Davis, T. P. Simon, editors. Biological assessment and criteria: Tools for water resource planning and decision making. Lewis Publishers, Boca Raton, Florida.

Hughes, R. M., D. P. Larsen, and J. M. Omernik. 1986. Regional reference sites: A method for assessing stream potentials. Environmental Management 10:629-635.

Irwin, R. J. 2006. Draft Part B lite QA/QC review checklist for aquatic vital sign monitoring protocols and SOPs. National Park Service, Water Resources Division, Fort Collins, Colorado. Distributed on Internet only at https://irma.nps.gov/DataStore/Reference/Profile/2225069

Isaak, D. J., C. H. Luce, B. E. Rieman, D. E. Nagel, E. E. Peterson, D. L. Horan, S. Parkes, and G. L. Chandler. 2010. Effects of climate change and wildfire on stream temperatures and salmonid thermal habitat in a mountain river network. Ecological Applications 20(5):1350-1371.

Isaak, D. J., E. Peterson, J. V. Hoef, S. Wenger, J. Falke, C. Torgersen, C. Sowder, A. Steel, M. J. Fortin, C. Jordan, A. Reusch, N. Som, and P. Monestiez. 2014. Applications of spatial statistical stream network models to stream data. Wiley Interdisciplinary Reviews - Water 1:277-294.

Isaak, D. J. S. J. Wenger, E. E. Peterson, J. M. Ver Hoef, S. W. Hostetler, C. H. Luce, J. B. Dunham, J. L. Kershner, B. B. Roper, D. E. Nagel, G. L. Chandler, S. P. Wollrab, S. L. Parkes, and D. L. Horan. 2016. NorWeST modeled summer stream temperature scenarios for the western U.S. U.S. Forest Service Research Data Archive, Fort Collins, Colorado. https://doi.org/10.2737/RDS-2016-0033.

Isaak, D. J., S. J. Wenger, and M. K. Young. 2017. Big biology meets microclimatology: Defining thermal niches of ectotherms at landscape scales for conservation planning. Ecological Applications. doi: 10.1002/eap.1501

Jackson, S., and W. Davis. 1995. Meeting the goal of biological integrity in water-resource programs of the U.S. Environmental Protection Agency. Journal of the North American Benthological Society 13:592-597.

Jenks G. F. 1967. The data model concept in statistical mapping. International Yearbook of Cartography 7:186-190.

Jeppesen, E., B. Kronvang, M. Meerhoff, M. Søndergaard, K. M. Hansen, H. E. Andersen, T. L. Lauridsen, L. Liboriussen, M. Beklioglu, A. Özen, and J. E. Olesen. 2009. Climate change effects on runoff, catchment phosphorus loading and lake ecological state, and potential adaptations. Journal of Environmental Quality 38(5):1930-1941.

Jessup, B., C. Hawkins, and J. Stribling. 2006. Biological indicators of stream condition in Montana using benthic macroinvertebrates. Prepared for the Montana Department of Environmental Quality by TetraTech, Inc., Owings Mills, Maryland, and the Western Center for Monitoring and Assessment of Freshwater Ecosystems, Utah State University, Logan.

Jones, L. A., C. C. Muhlfeld, L. A. Marshall, B. L. McGlynn, and J. L. Kershner. 2014. Estimating thermal regimes of bull trout and assessing the potential effects of climate warming on critical habitats. River Research and Applications 30(2):204-216.

Jordan, S., J. J. Giersch, C. C. Muhlfeld, S. Hotaling, L. Fanning, T. H. Tappenbeck, and G. Luikart. 2016. Loss of genetic diversity and increased subdivision in an endemic alpine stonefly threatened by climate change. PloS one 11(6):p.e0157386

Junk, W., P. B. Bayley, and R. E. Sparks. 1989. The flood pulse concept in river-floodplain systems. Proceedings of the International Large River Symposium (LARS). Canadian Special Publications in Fisheries and Aquatic Sciences 106:110-127.

Karr, J. A., and D. R. Dudley. 1981. Ecological perspectives on water quality goals. Environmental Management 5:55-68.

Karr, J. R. 1991. Biological integrity - a long-neglected aspect of water-resource management. Ecological Applications 1:66-84.

Karr, J. R., and E. W. Chu. 1997. Biological monitoring: Essential foundation for ecological risk assessment. Human and Ecological Risk Assessment 3:993-1004.

Karr, J. R., and E. W. Chu. 1999. Restoring life in running waters: better biological monitoring. Island Press, Washington, D.C.

Karr, J. R., and B. L. Kerans. 1992. Components of biological integrity: Their definition and use in development of an invertebrate IBI. In Midwest Pollution Control Biologists Meeting, Chicago, Ill., 1991, Proceedings. U.S. Environmental Protection Agency, Region V, EPA-905/R-92-003.

Kasahara, T., and S. M. Wondzell. 2003. Geomorphic controls on hyporheic exchange flow in mountain

streams. Water Resources Research 39(1), 1005. doi: 10.1029/2002WR001386.

Kaufmann, P. R. (ed.). 1993. Physical habitat. Pp. 59_69 in R. M. Hughes (ed.). Stream Indicator and Design Workshop. EPA/600/R_93/138. U.S. Environmental Protection Agency, Office of Research and Development, Corvallis, Oregon.

Kaufmann, P. R., J. M. Faustini, D. P. Larsen, and M. A. Shirazi. 2008. A roughness-corrected index of relative bed stability for regional stream surveys. Geomorphology 99:150-70.

Kaufmann P. R., and R. M. Hughes. 2006. Geomorphic and anthropogenic influences on fish and amphibians in Pacific Northwest coastal streams. American Fisheries Society Symposium 48:429-455.

Kaufmann, P. R., D. P. Larsen, and J. M. Faustini. 2009. Bed stability and sedimentation associated with human disturbances in Pacific Northwest streams. Journal of the American Water Resources Association 45:434-459.

Kaufmann, P. R., P. Levine, E. G. Robison, C. Seeliger, and D. Peck. 1999. Quantifying physical habitat in wadeable streams. U.S. Environmental Protection Agency, Washington, D.C.

Kaufmann, P. R., and T. R. Whittier. 1997. Habitat assessment. Pages 5-1 to 5-26 in J. R. Baker, D. V. Peck, and D. W. Sutton (eds.). Environmental Monitoring and Assessment Program -surface waters: Field operations manual for lakes. EPA/620/R-97/001. U.S. Environmental Protection Agency, Washington, D.C.

Kaushal, S. S., G. E. Likens, R. M. Utz, M. L. Pace, M. Grese, and M. Yepsen. 2013. Increased river alkalinization in the Eastern US. Environmental Science and Technology 47(18):10302-10311.

Kelly, V. R., G. M. Lovett, K. C. Weathers, S. E. Findlay, D. L. Strayer, D. J. Burns, and G. E. Likens. 2007. Long-term sodium chloride retention in a rural watershed: legacy effects of road salt on streamwater concentration. Environmental Science and Technology 42(2):410-415.

Kerans, B. L., and J. R. Karr. 1994. A benthic index of biotic integrity (B-IBI) for rivers of the Tennessee Valley. Ecological Applications 4(4):768-785.

Kershner, J. L., B. B. Roper, N. Bouwes, R. C. Henderson, and E. K. Archer. 2004. An analysis of stream habitat conditions in reference and managed watersheds on some federal lands within the Columbia River Basin. North American Journal of Fisheries Management 24:1363-1375.

Kincaid, T. M., and A. R. Olsen. 2015. spsurvey: Spatial survey design and analysis. R package version 3.1. https://cran.r-project.org/web/packages/spsurvey/index.html

King, R. S., M. E. Baker, D. F. Whigham, D. E. Weller, T. E. Jordan, P. F. Kazyak, and M. K. Hurd. 2005. Spatial considerations for linking watershed land cover to ecological indicators in streams. Ecological Applications 15(1):137-153.

Kishi, D., M. Murakami, S. Nakano, and K. Maekawa. 2005. Water temperature determines strength of top-down control in a stream food web. Freshwater Biology 50(8):1315-1322.

Knowles, N., M. D. Dettinger, and D. R. Cayan. 2006. Trends in snowfall versus rainfall in the western United States. Journal of Climate 19:4545-4559.

Kociolek, J. P., Q. M. You, Q. X. Wang, and Q. Liu. 2015. A consideration of some interesting freshwater gomphonemoid diatoms from North America and China, and the description of *Gomphosinica* gen. nov. Nova Hedwigia, Beihefte 144:175-198.

Kruskal, W. 1987. Relative importance by averaging over orderings. The American Statistician 41:6-10.

Kumar, S., S. A. Spaulding, T. J. Stohlgren, K. A. Hermann, T. S. Schmidt, and L. L. Bahls. 2009. Potential habitat distribution for the freshwater diatom *Didymosphenia geminata* in the continental U.S. Frontiers in Ecology and the Environment 7:415-420.

Kusnierz, P., A. Welch, and D. Kron. 2013. The Montana Department of Environmental Quality sediment assessment method: considerations, physical and biological parameters, and decision making. Montana Dept. of Environmental Quality, Helena.

Lange-Bertalot, H. 1979. Pollution tolerance of diatoms as a criterion for water quality estimation. Nova Hedwigia 64:285-304.

Larsen, W. A., and S. J. McCleary. 1972. The use of partial residual plots in regression analysis. Technometrics 14(3):781-790.

Lazorchak, J. M., D. J. Klemm and D. V. Peck (eds.). 1998.

Environmental Monitoring and Assessment Program – surface waters: field operations and methods for measuring the ecological condition of wadeable streams. EPA/620/R-94/004F. U.S. Environmental Protection Agency, Office of Research and Development, Washington, D.C.

Lester, R. E., W. Wright, and M. Jones-Lennon. 2007. Does adding wood to agricultural streams enhance biodiversity? An experimental approach. Marine and Freshwater Research 58(8):687-698.

Li, L., B. Zheng, and L. Liu. 2010. Biomonitoring and bioindicators used for river ecosystems: definitions, approaches and trends. Procedia Environmental Sciences 2:1510-1524.

Likens, G. E., F. H. Bormann, R. S. Pierce, J. S. Eaton, and N. M. Johnson. 1977. Biogeochemistry of a forested ecosystem. Springer-Verlag, New York.

Likness, G. A., and W. R. Gould. 1987. The distribution, habitat, and population characteristics of fluvial Arctic grayling (*Thymallus arcticus*) in Montana. Northwest Science 61: 122-129.

Lindeman, R. H., P. F. Merenda, and R. Z. Gold. 1980. Introduction to bivariate and multivariate analysis. Scott, Foresman, Glenview Illinois.

Lisle, T. E. 1982. Effects of aggradation and degradation on riffle-pool morphology in natural gravel channels, northwestern California. Water Resources Research 18(6):1643-1651.

Lisle, T. E., and S. Hilton. 1991. Fine sediment in pools: An index of how sediment is affecting a stream channel. R-5 Fish Habitat Relationships Technical Bulletin 6:1-6.

Long, B. 2000. Conserving an international treasure: the trans-boundary Flathead. Montana Wilderness Association, Helena, Montana.

Lowe, R. L. 1974. Environmental requirements and pollution tolerance of freshwater diatoms. United States Environmental Protection Agency, National Environmental Research Center, Cincinnati, Ohio.

MacDonald, L. H., A. W. Smart, and R. C. Wissmar. 1991. Monitoring guidelines to evaluate effects of forestry activities on streams in the Pacific Northwest and Alaska. EPA 910/9-91-001. Prepared for Region 10, U.S. Environmental Protection Agency, Seattle, Washington.

MacIsaac, H. J., and R. Rocha. 1995. Effects of suspended clay on zebra mussel (*Dreissena polymorpha*) faeces and pseudofaeces production. Archiv für Hydrobiologie 135:53-64.

Mack, R. N. 2000. Assessing the extent, status and dynamism in plant invasions: current and emerging approaches. Pp. 141-168 in H. A. Mooney and R. J. Hobbs (editors). The impact of global change on invasive species. Island Press, Washington, D.C.

Madej, M. A. 2001. Development of channel organization and roughness following sediment pulses in single-thread, gravel bed rivers. Water Resources Research 37(8): 2259-2272.

Mast, M. A. 2007. Assessment of historical water-quality data for National Park units in the Rocky Mountain Network, Colorado and Montana, through 2004. U.S. Geological Survey Scientific Investigations Report 2007–5147.

Mast, M. A. 2013. Evaluation of stream chemistry trends in US Geological Survey reference watersheds, 1970–2010. Environmental Monitoring and Assessment 185(11):9343-9359.

Mast, M. A., D. H. Campbell, D. P. Krabbenhoft, and H. E. Taylor. 2005. Mercury transport in a high-elevation watershed in Rocky Mountain National Park, Colorado. Water Air and Soil Pollution 164:21-42.

Mast, M. A., and D. W. Clow. 2008. Effects of 2003 wildfires on stream chemistry in Glacier National Park, Montana. Hydrological Processes 22(26):5013-5023.

McBride, M., and D. B. Booth. 2005. Urban impacts on physical stream condition: effects of spatial scale, connectivity, and longitudinal trends. Journal of the American Water Resources Association 565-580.

McCune, B., and J. B. Grace. 2002. Analysis of ecological communities. MjM Software Design, Gleneden Beach, Oregon.

McKay L., T. Bondelid, T. Dewald, J. Johnston, R. Moore, and A. Rea. 2014. NHDPlus Version 2: User Guide. U.S. Environmental Protection Agency. https://nctc.fws.gov/courses/references/tutorials/geospatial/CSP7306/Readings/NHDPlusV2_User_Guide.pdf , accessed September, 2016.

McKernan, C., D. J. Cooper, and E. W. Schweiger. 2018. Glacial loss and its effect on riparian vegetation of

alpine streams. Freshwater Biology 2018;00:1-12. https://doi.org/10.1111/fwb.13088

McKnight, D. M., R. Harnish, R. L. Wershaw, J. S. Baron, and S. Schiff. 1997. Chemical characteristics of particulate, colloidal, and dissolved organic material in Loch Vale Watershed, Rocky Mountain National Park. Biogeochemistry 36:99-124.

Merritt, D. M., and E. E. Wohl. 2002. Processes governing hydrochory along rivers: hydraulics, hydrology, and dispersal phenology. Ecological Applications 12:1071-1087.

Mitchell, B. R., G. L. Tierney, E. W. Schweiger, K. M. Miller, D. Faber-Langendoen, and J. B. Grace. 2014. Getting the message across: using ecological integrity to communicate with resource managers. In G. R. Guntenspergen (ed.), Application of threshold concepts in natural resource decision making. doi: 10.1007/978-1-4899-8041-0_10. Springer Science+Business Media, LLC.

Monahan, W. B., and N. A. Fisichelli. 2014. Climate exposure of US National Parks in a new era of change. Plos One 9(7):1.

Monahan, W. B., and J. E. Gross. 2012. Upstream landscape dynamics of US National Parks with implications for water quality and watershed management. Pages 27-50 in Abiud Kaswamila (ed.), Sustainable natural resources management. InTech. doi: 10.5772/1945.

Montana Department of Environmental Quality (Montana DEQ). 2002. Administrative Rules of Montana Environmental Quality, Chapter 30 Water Quality, Subchapter 6 Surface Water Quality Standards and Procedures. Montana Department of Environmental Quality, Helena.

Montana Department of Environmental Quality (Montana DEQ). 2009. Ecological Data Application System (EDAS) Version MT 3.3.2k. Tetra Tech, Inc.

Montana Department of Environmental Quality (Montana DEQ). 2011. Department Circular Deq-12, Parts A and B Montana base numeric nutrient standards and nutrient standards variances. Montana Department of Environmental Quality, Helena.

Montana Department of Environmental Quality (Montana DEQ). 2012a. Sample collection, sorting, taxonomic identification, and analysis of benthic macroinvertebrate communities standard operating procedure. Montana Department of Environmental Quality, Helena.

Montana Department of Environmental Quality (Montana DEQ). 2012b. Water Quality Planning Bureau field procedures manual for water quality assessment monitoring, version 3.0. Montana Department of Environmental Quality, Helena.

Montana Department of Environmental Quality (Montana DEQ). 2016. Montana final 2016 water quality integrated report. Document number WQPBIMTSTR-011f. Montana Department of Environmental Quality, Helena.

Montana Department of Environmental Quality (Montana DEQ), Water Quality Division, Water Quality Planning Bureau, Water Quality Standards and Modeling Section. 2017. DEQ-7 Montana Numeric Water Quality Standards. Montana Department of Environmental Quality, Helena.

Montana Fish, Wildlife and Parks (MFWP). 2008. Statewide integrated noxious weed management plan. Montana Fish, Wildlife and Parks, Helena.

Morales, E. A. 2005. Observations of the morphology of some known and new fragilarioid diatoms (Bacillariophyceae) from rivers in the USA. Phycological Research 53:113-133.

Morales, E. A., K. M. Manoylov, and L. L. Bahls. 2012. *Fragilariforma horstii* sp. nov. (Bacillariophyceae) a new araphid species from the northern United States of America. Nova Hedwigia, Beiheft 141:141-154.

Moyle, P. B. 1976. Fish introductions in California: History and impacts on native fishes. Biological Conservation 9: 101-118.

Muhlfeld, C. C., and D. H. Bennett. 2001. Summer habitat use by Columbia River Redband Trout in the Kootenai River Drainage, Montana. North American Journal of Fisheries Management 21(1): 223-235.

Muhlfeld, C. C, J. J. Giersch, F. R. Hauer, G. T. Pederson, G. Luikart, D. P. Peterson, C. C. Downs, and D. B. Fagre. 2011. Climate change links fate of glaciers and an endemic alpine invertebrate. Climatic Change 106:337-345 doi: 10.1007/s10584-011-0057-1.

Muhlfeld, C. C., and B. Marotz. 2005. Seasonal movement and habitat use by sub-adult bull trout in the upper Flathead River system, Montana. North American

Journal of Fisheries Management 25:797-810.

Murtaugh, P. A. 2014. In defense of P values. Ecology 95(3):611-617.

Naiman, R. J., C. A. Johnston, and J. C. Kelley. 1988. Alteration of North American streams by beaver. Bioscience 387:753-762.

National Park Service (NPS). 1999. Final General Management Plan and Environmental Impact Statement, Record of Decision, and Summary, Glacier National Park. https://parkplanning.nps.gov/document.cfm?parkID=61&projectID=39894&documentID=44643 (accessed September 2017)

National Park Service (NPS). 2002. Environmental Assessment Water System Rehabilitation for Apgar & Park Headquarters Glacier National Park, Montana. National Park Service Unpublished Report available from Glacier National Park, West Glacier, Montana.

National Park Service (NPS). 2006a. Glacier National Park weather webpage. http://www.nps.gov/glac/planyourvisit/weather.htm (accessed September 2017).

National Park Service (NPS). 2006b. Management Policies 2006. U.S. Department of the Interior, National Park Service, Washington, D.C.

National Park Service (NPS). 2007. Great Sand Dunes National Park and Preserve Final General Management Plan/Wilderness Study/Environmental Impact Statement – April 2007. Plan and associated summary document available online at https://parkplanning.nps.gov/document.cfm?parkID=67&projectId=11015&documentID=19561.

National Park Service (NPS). 2017. Montana: Hungry Horse Dam webpage. Discover our Shared Heritage Travel Itinerary Series. https://www.nps.gov/articles/montana-hungry-horse-dam.htm.

Nilsson, C., and M. Svedmark. 2002. Basic principles and ecological consequences of changing water regimes: riparian plant communities. Environmental Management 30:468-480.

Nimick, D. A. 2003. Diurnal variation in trace-metal concentrations in streams. U.S. Geological Survey Fact Sheet FS-086-03, page 4. https://pubs.usgs.gov/fs/fs08603/pdf/fs08603.pdf

Ode, P. R., C. P. Hawkins, and R. D. Mazor, R.D. 2008. Comparability of biological assessments derived from predictive models and multimetric indices of increasing geographic scope. Journal of the North American Benthological Society 27:967-985.

Olsen, A. R., and D. V. Peck. 2008. Monitoring design and extent estimates for the Wadeable Stream Assessment. Journal of the North American Benthological Society 27:822-836.

Olsen, A. R., J. Sedransk, D. Edwards, C. A. Gotway, W. Liggett, S. Rathbun, K. E. Reckhow, and L. J. Young. 1999. Statistical issues for monitoring ecological and natural resources in the United States. Environmental Monitoring and Assessment 54:1-45.

Overton, W. S., and S. V. Stehman. 1996. Desirable design characteristics for long-term monitoring of ecological variables. Environmental and Ecological Statistics 3:349-361.

Palmer, C. M. 1969. A composite rating of algae tolerating organic pollution. Journal of Phycology 5(1):78-82.

Palmer, M. A., and E. S. Bernhardt. 2006. Hydroecology and river restoration: ripe for research and synthesis. Water Resources Research 42.

Peck, D. V., J. M. Lazorchak, and D. J. Klemm (eds.). 2006. Environmental monitoring and assessment program, surface waters—western pilot study-field operations manual for wadeable streams. EPA/620/R–06/003. U.S. Environmental Protection Agency, Washington, D.C.

Pederson, G. T., L. J. Graumlich, D. B. Fagre, T. Kipfer, and C. C. Muhlfeld. 2010. A century of climate and ecosystem change in Western Montana: what do temperature trends portend? Climatic Change 98:133-154.

Peters, N. E. 1984. Evaluation of environmental factors affecting yields of major dissolved ions of streams in the United States. U.G. Geological Survey Water-Supply Paper No. 2228. https://pubs.usgs.gov/wsp/2228/report.pdf

Peterson, E. E., and J. M. Ver Hoef. 2010. A mixed-model moving-average approach to geostatistical modeling in stream networks. Ecology 91:644-651.

Peterson E. E., J. M. Ver Hoef, D. J. Isaak, J. A. Falke., M. J. Fortin, C. Jordan, K. McNyset, P. Monestiez, A. S. Ruesch, A. Sengupta, N. Som, A. Steel, D. M. Theobald, C. T. Torgersen, and S. J. Wenger. 2013. Modeling dendritic ecological networks in space: an integrated network perspective. Ecology Letters 16:707-719.

Platts, W. S., W. F. Megahan, and G. W. Minshall. 1983. Methods for evaluating stream, riparian and biotic conditions. Gen. Tech. Rep. INT-138. U.S. Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah.

Poff, N. L., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Prestegaard, B. D. Richter, R. E. Sparks, and J. C. Stromberg. 1997. The natural flow regime. BioScience 47(11):769-784.

Poff, N. L., and J. D. Ward. 1989. Implications of streamflow variability and predictability for lotic community structure: A regional analysis of streamflow patterns. Canadian Journal of Fisheries and Aquatic Sciences 46:1805-1818.

Prato, T., and D. Fagre. 2007. Achieving ecosystem sustainability. Pp. 302-311 in Sustaining Rocky Mountain landscapes: science, policy and management of the Crown of the Continent Ecosystem. Resources for the Future Press, Washington, D.C.

Prescott, G. W., and G. E. Dillard. 1979. A checklist of algal species reported from Montana, 1891 to 1977. Monograph No. 1. Montana Academy of Sciences, Supplement to the Proceedings 38.

PRISM Climate Group, Oregon State University. 2017. PRISM Climate Data website. Available at http://prism.oregonstate.edu (accessed September 2017).

Qian, S. S., R. S. King, and C. J. Richardson. 2003. Two statistical methods for the detection of environmental thresholds. Ecological Modelling 166(1):87-97.

R Development Team. 2014. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Rahel, F. J., and J. D. Olden. 2008. Assessing the effects of climate change on aquatic invasive species. Conservation Biology 22:521-533.

Reddy, K. R., R. H. Kadlec, E. Flaig, and P. M. Gale. 1999. Phosphorus retention in streams and wetlands: a review. Critical Reviews in Environmental Science and Technology 29(1):83-146.

Relyea, C. D., G. W. Minshall, and R. J. Danehy. 2000. Stream insects as bioindicators of fine sediment. Proceedings of the Water Environment Federation 2000(6):663-686.

Relyea, C. D., G. W. Minshall, and R. J. Danehy. 2012. Development and validation of an aquatic fine sediment biotic index. Environmental Management 49(1):242-252.

Resh, V. H. 2008. Which group is best? Attributes of different biological assemblages used in freshwater biomonitoring. Environmental Monitoring and Assessment 138(1-3):131-138.

Riitters, K., J. Wickham, R. O'Neill, B. Jones, and E. Smith. 2000. Global-scale patterns of forest fragmentation. Conservation Ecology 4(2):3. http://www.consecol.org/vol4/iss2/art3/ (accessed September 2017).

Ringold, P. L., T. K. Magee, and D. V. Peck. 2008. Twelve invasive plant taxa in US western riparian ecosystems. Journal of the North American Benthological Society 27(4):949-966.

Rinne, J. 1988. Effects of livestock grazing exclosure on aquatic macroinvertebrates in a montane stream, New Mexico. Great Basin Naturalist 48(2):146-153.

Robison, E. G., and R. L. Beschta, 1989. Estimating Stream Cross Sectional Area from Wetted Width and Thalweg Depth. Phys. Geogr. 10(2): 190–198.

Rood, S. B., G. M. Samuelson, J. K. Weber, K. A. Wywrot. 2005. Twentieth-century decline in stream flows from the hydrographic apex of North America. Journal of Hydrology 306(2005):215-233.

Rosgen, D. L. 1994. A classification of natural rivers. Catena 22:169-199.

Schindler, D. W. 1988. Effects of acid rain on freshwater ecosystems. Science (Washington) 239(4836):149-157.

Schoolmaster, D. R. Jr., J. B. Grace, and E. W. Schweiger. 2012. A general theory of multimetric indices and their properties. Methods in Ecology and Evolution 3:773-781. doi: 10.1111/j.2041-210X.2012.00200.x

Schoolmaster, D. R. Jr., J. B. Grace, E. W. Schweiger, B. R. Mitchell, and G. R. Guntenspergen. 2012. A causal examination of the effects of confounding factors on multimetric indices. Ecological Indicators 29:411-419.

Schweiger, E. W., I. W. Ashton, C. C. Muhlfeld, L. A. Jones, and L. L. Bahls. 2011. The distribution and abundance of a nuisance native alga, *Didymosphenia geminata*, in streams of Glacier National Park: climate drivers and management implications. Park Science 28:88-91.

Schweiger, E. W., M. Britten and Others. In preparation a. Glacier National Park stream ecological integrity 2007

– 2016 sentinel site trend report. Natural Resource Report NPS/ROMN/NRR—201X/XXX. National Park Service, Fort Collins, Colorado.

Schweiger, E. W., M. Britten and Others. In preparation b. Rocky Mountain National Park wetland ecological integrity Rocky Mountain Inventory and Monitoring Network 2007 – 201X data report. Natural Resource Report NPS/ROMN/NRR—201X/XXX. National Park Service, Fort Collins, Colorado.

Schweiger, E. W., J. B. Grace, D. Cooper, B. Bobowski, and M. Britten. 2016. Using structural equation modeling to link human activities to wetland ecological integrity. Ecosphere 7(11):e01548. 10.1002/ecs2.1548.

Schweiger, E. W., L. O'Gan, E. Borgman, and M. Britten. 2015. Rocky Mountain Network stream ecological integrity monitoring protocol: Narrative, version 1.0. Natural Resource Report NPS/ROMN/NRR—2015/1101. National Park Service, Fort Collins, Colorado.

Schweiger, E. W., L. O'Gan, E. Borgman, M. Britten, and D. Shorrock. 2016. Rocky Mountain Network stream ecological integrity monitoring protocol: Standard operating procedures, version 1.0. Natural Resource Report NPS/ROMN/NRR—2016/1132. National Park Service, Fort Collins, Colorado.

Schweiger, E. W., L. O'Gan, D. Shorrock, and M. Britten. 2014a. Stream ecological integrity at Grant-Kohrs Ranch National Historic Site: Rocky Mountain Inventory & Monitoring Network 2008-2010 stream monitoring report. Natural Resource Technical Report NPS/ ROMN/NRTR—2014/881. National Park Service, Fort Collins, Colorado.

Schweiger, E. W., L. O'Gan, D. Shorrock, and M. Britten. 2014b. Stream ecological integrity at Little Bighorn Battlefield National Monument: Rocky Mountain Inventory & Monitoring Network 2007-2010 stream monitoring report. Natural Resource Technical Report NPS/ROMN/NRTR—2014/882. National Park Service, Fort Collins, Colorado.

Seastedt, T. R., W. D. Bowman, T. N. Caine, D. McKnight, A. Townsend, and M. W. Williams. 2004. The landscape continuum: A model for high-elevation ecosystems. Bioscience 54:111-121.

Shannon, C. E. 1948. A mathematical theory of communication. The Bell System Technical Journal 27:379-423 and 623-656.

Simon, A., and M. Rinaldi. 2006. Disturbance, stream incision, and channel evolution: The roles of excess transport capacity and boundary materials in controlling channel response. Geomorphology 79(3):361-383.

Simons, D. B., and F. Senturk. 1977. Sediment transport technology. Water Resources Publications, Fort Collins, Colorado.

Sinokrot, B. A., and H. G. Stefan. 1994. Stream water-temperature sensitivity to weather and bed parameters. Journal of Hydraulic Engineering 120(6):722-736.

Spaulding, S., and W. Elwell. 2007. Increase in nuisance blooms and geographic expansion of the freshwater diatom *Didymosphenia geminata*: Recommendations for response. EPA Region 8 and Federation of Fly Fishers, Denver, Colorado.

Spaulding, S. A., D. J. Lubinski, and M. Potapova. 2010. Diatoms from the Crown of the Continent webpage. http://westerndiatoms.colorado.edu/about/project/1826/diatoms_from_the_crown_of_the_continent (accessed on 27 March, 2017).

Spellerberg, I.A.N. 1998. Ecological effects of roads and traffic: a literature review. Global Ecology and Biogeography 7(5):317-333.

Stack, W. R., and R. L. Beschta. 1989. Factors influencing pool morphology in Oregon coastal streams. Pp. 401-411 in W. W. Woessner and D. F. Potts (eds.), Headwaters Hydrology Symposium, Missoula, Montana. American Water Resources Association, Bethesda, Maryland.

Stamp, J. D., A. T. Hamilton, L. Zheng, and B. G. Bierwagen. 2010. Use of thermal preference metrics to examine state biomonitoring data for climate change effects. Journal of the North American Benthological Society 29(4):1410-1423.

Stanford, J. A., J. V. Ward, and B. K. Ellis. 1994. Ecology of the alluvial aquifers of the Flathead River, Montana (USA). Pp. 367-390 in J. Givert, D. L. Danielopol, and J. A. Stanford (eds.), Groundwater ecology. Academic Press, San Diego, California.

Steedman, R. J. 1988. Modification and assessment of an index of biotic integrity to quantify stream quality in southern Ontario. Canadian Journal of Fisheries and Aquatic Sciences 45:492-501.

Stevens, D. L. 1997. Variable density grid-based sampling designs for continuous spatial populations. Environmetrics 8:167-195.

Stevens, D. L., and A. R. Olsen. 2004. Spatially balanced sampling of natural resources. Journal of the American Statistical Association 99:262-278.

Stevenson, R. J., and J. P. Smol. 2003. Use of algae in environmental assessments. Pp. 775-804 in J. D. Wehr and R. G. Sheath, (eds.), Freshwater algae in North America: Classification and ecology. Academic Press, San Diego, California.

Stoddard, J. L., A. T. Herlihy, D. V. Peck, R. M. Hughes, T. R. Whittier, and E. Tarquinio. 2008. A process for creating multimetric indices for large-scale aquatic surveys. Journal of the North American Benthological Society 27:878-891.

Stoddard, J. L., D. P. Larsen, C. P. Hawkins, R. K. Johnson, and R. H. Norris. 2006. Setting expectations for the ecological condition of streams: The concept of reference condition. Ecological Applications 16:1267-1276.

Stoddard, J. L., D. V. Peck, S. G. Paulsen, J. Van Sickle, C. P. Hawkins, A. T. Herlihy, R. M. Hughes, P. R. Kaufmann, D. P. Larsen, G. Lomnicky, A. R. Olsen, S. A. Peterson, P. L. Ringold, and T. R. Whittier. 2005. An ecological assessment of western streams and rivers. U.S. Environmental Protection Agency, Washington, D.C.

Stoddard, J. L., J. Van Sickle, A. T. Herlihy, J. Brahney, S. Paulsen, D. V. Peck, R. Mitchell, and A. I. Pollard. 2016. Continental-scale increase in lake and stream phosphorus: Are oligotrophic systems disappearing in the United States? Environmental Science and Technology 50(7):3409-3415.

Stottlemyer, R., C. A. Troendle, and D. Markowitz. 1997. Change in snowpack, soil water, and streamwater chemistry with elevation during 1990, Fraser Experimental Forest, Colorado. Journal of Hydrology 195:114-136.

Strahler, A. N. 1952. Dynamic basis of geomorphology. Geological Society of America Bulletin 63:923-938.

Strahler, A. N. 1957. Quantitative analysis of watershed geomorphology. Eos, Transactions American Geophysical Union 38(6):913-920.

Strayer, D. L., R. E. Beighley, L. C. Thompson, S. Brooks, C. Nilsson, G. Pinay, and R. J. Naiman. 2003. Effects of land cover on stream ecosystems: roles of empirical models and scaling issues. Ecosystems 6(5):407-423.

Suplee, M. W., and R. Sada de Suplee. 2011. Assessment methodology for determining wadeable stream impairment due to excess nitrogen and phosphorus levels. Montana Dept. of Environmental Quality, Helena.

Suplee, M., R. S. de Suplee, D. Feldman, and T. Laidlaw. 2005. Identification and assessment of Montana reference streams: A follow-up and expansion of the 1992 benchmark biology study. Montana Dept. of Environmental Quality, Helena.

Suplee, M. W., and V. Watson. 2013. Scientific and technical basis of the numeric nutrient criteria for Montana's wadeable streams and rivers—update 1. Montana Dept. of Environmental Quality, Helena.

Suplee, M. W., V. Watson, A. Varghese, and J. Cleland, 2008. Scientific and technical basis of the numeric nutrient criteria for Montana's wadeable streams and rivers, and addendums. Montana Department of Environmental Quality Helena.

Suttle, K. B., M. E. Power, J. M. Levine, and C. McNeeley. 2004. How fine sediment in riverbeds impairs growth and survival of juvenile salmonids. Ecological Applications 14(4):969-974.

Teply, M. 2010a. Diatom biocriteria for Montana streams. Montana Department of Environmental Quality, Helena.

Teply, M. 2010b. Interpretation of periphyton samples from Montana streams. Montana Department of Environmental Quality, Helena.

Teply, M., and L. Bahls. 2005. Diatom biocriteria for Montana streams. Montana Department of Environmental Quality, Helena.

Teply, M., and L. Bahls. 2006. Interpretation of periphyton samples for Montana streams - Middle Rockies Ecoregion. Montana Department of Environmental Quality, Helena.

Theobald, D. M., J. B. Norman, and P. Newman. 2010. Estimating visitor use of protected areas by modeling accessibility: A case study in Rocky Mountain National Park, Colorado. Journal of Conservation Planning 6:1-20.

Theobald, D. M. 2005. Landscape patterns of exurban growth in the USA from 1980 to. Ecology and Society 10(1):32.

Thunqvist, E. L. 2004. Regional increase of mean chloride concentration in water due to the application of deicing salt. Science of the Total Environment 325(1):29-37.

Trombulak, S. C., and C. A. Frissell. 2000. Review of ecological effects of roads on terrestrial and aquatic communities. Conservation Biology 14(1):18-30.

U.S. Census Bureau. 2017. TIGER/Line Shapefiles, 2010. Available at https://www.census.gov/geo/maps-data/data/tiger-line.html (accessed June, 2017).

U.S. Department of Agriculture (USDA). 2017. Plants Database. Introduced, Invasive, and Noxious Plants, Montana State-listed Noxious Weeds webpage. https://plants.usda.gov/java/noxious?rptType=State&statefips=30. (accessed on 3/16/2017).

U.S. Department 0f Agriculture (USDA). 2005. National Agriculture Imagery Program (NAIP). https://www.fsa.usda.gov/about-fsa/index. (accessed on 9/26/2017).

U.S. Environmental Protection Agency (EPA). 1996. Sampling ambient water for trace metals at EPA water quality criteria levels. U.S Environmental Protection Agency, Office of Water, Washington, D.C.

U.S. Environmental Protection Agency (EPA). 2002. National recommended water quality criteria: 2002. EPA-822-R-02-047. U.S Environmental Protection Agency, Office of Water, Washington, D.C.

U.S. Environmental Protection Agency (EPA). 2008. Climate change effects on stream and river biological indicators: A preliminary analysis. Global Change Research Program, National Center for Environmental Assessment, Washington, D.C.; EPA/600/R-07/085. Available from the National Technical Information Service, Springfield, Virginia, and online at http://www.epa.gov/ncea.

U.S. Environmental Protection Agency (EPA). 2009. National recommended water quality criteria. United States Office of Water, Washington, D.C.

U.S. Environmental Protection Agency (EPA). 2015. National wetland condition assessment: technical report. EPA 843-R-15-006. U.S Environmental Protection Agency, Washington, D.C.

U.S. Environmental Protection Agency (EPA). 2016a. Definition and procedure for the determination of the method detection limit, revision 2. 821-R-16-006. U.S Environmental Protection Agency, Office of Water, Washington, D.C.

U.S. Environmental Protection Agency (EPA). 2016b. National aquatic resource surveys. National rivers and streams assessment 2008-2009 (data and metadata files). Available from U.S. EPA website: http://www.epa.gov/national-aquatic-resource-surveys/data-national-aquatic-resource-surveys (accessed 2017-0203).

U.S. Environmental Protection Agency (EPA), Office of Water and Office of Research and Development. 2016c. National rivers and streams assessment 2008-2009: A collaborative survey. EPA/841/R-16/007. U.S Environmental Protection Agency, Washington, D.C. March 2016. https://www.epa.gov/sites/production/files/2016-03/documents/nrsa_0809_march_2_final.pdf

U.S. Environmental Protection Agency (EPA). 2017. Secondary drinking water standards: guidance for nuisance chemicals. https://www.epa.gov/dwstandardsregulations/secondary-drinking-water-standards-guidance-nuisance-chemicals.

U.S. Fish and Wildlife Service (USFWS). 1998. A framework to assist in making Endangered Species Act determinations of effect for individual or grouped actions at the bull trout subpopulation watershed scale. https://www.fws.gov/montanafieldoffice/Endangered_Species/Bull_Trout_consultation/matrix.pdf

U.S. Geological Survey (USGS). 2017a. National Elevation Dataset (NED). Online. https://lta.cr.usgs.gov/NED (accessed June, 2017).

U.S. Geological Survey (USGS). 2017b. National hydrography dataset. Online. http://nhd.usgs.gov/ (accessed June, 2017).

U.S. Geological Survey (USGS). 2017c. Roads c2016 in the Crown of the Continent. Online. https://www.sciencebase.gov/catalog/item/579a38d9e4b0589fa1c86fdd (accessed July, 2017).

Van Sickle, J. 2008. An index of compositional dissimilarity between observed and expected assemblages. Journal of the North American Benthological Society 27:227-235.

Van Sickle, J., D. P. Larsen, and C. P. Hawkins. 2007.

Exclusion of rare taxa affects performance of the O:E index in bioassessments. Journal of the North American Benthological Society 26(2):319-331.

Vannote, R. L., G. W. Minshall, K. W. Cummins, J. R. Sedell, and C. E. Cushing. 1980. The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences 37:130-137.

Venables, W., and B. Ripley. 2002. Modern applied statistics with S. Fourth edition. Springer, New York. http://www.stats.ox.ac.uk/pub/MASS4.

Ver Hoef, J. M., and E. E. Peterson. 2010. A moving average approach for spatial statistical models of stream networks. Journal of the American Statistical Association 105:6-18.

Ver Hoef, J. M., E. E. Peterson, and D. Theobald. 2006. Spatial statistical models that use flow and stream distance. Environmental and Ecological Statistics 13:449-464.

Waite, I. R., A. T. Herlihy, D. P. Larsen, and D. J. Klemm. 2000. Comparing strengths of geographic and nongeographic classifications of stream benthic macroinvertebrates in the Mid-Atlantic Highlands, USA. Journal of the North American Benthological Society 19(3):429-441.

Walking Shadow Ecology. 2017. Climate data summarizer, version 4.4. Online. http://www.yellowstoneecology.com/research/COOP_data.html (accessed September 2017).

Wang, L., and P. Kanehl. 2003. Influences of watershed urbanization and instream habitat on macroinvertebrates in cold water streams. Journal of the American Water Resources Association 39(5):1181-1196.

Waters, T. F. 1995. Sediment in streams: sources, biological effects, and controls. Monograph - American Fisheries Society: 7.

Weber, C. I. (ed.). 1973. Biological field and laboratory methods for measuring the quality of surface waters and effluents. EPA-670/4-73-001. U.S. Environmental Protection Agency, Cincinnati, Ohio.

Welsh, H. H., and L. M. Ollivier. 1998. Stream amphibians as indicators of ecosystem stress: a case study from California's redwoods. Ecological Applications 8(4):1118-1132.

Werner, D. 1977. Silicate metabolism. The Biology of Diatoms 13:111-149.

Whiles, M. R., and W. K. Dodds. 2002. Relationships between stream size, suspended particles, and filter-feeding macroinvertebrates in a Great Plains drainage network. Journal of Environmental Quality 31(5):1589-1600.

White, D. S., C. H. Elzinga, and S. P. Hendricks. 1987. Temperature patterns within the hyporheic zone of a northern Michigan river. Journal of the North American Benthological Society 6:85-91.

Wilcock, P. R. 1997. The components of fractional transport rate. Water Resources Research 33(1):247-258.

Wilcock, P. R. 1998. Two-fraction model of initial sediment motion in gravel-bed rivers. Science 280:410-412.

Winter, D., and L. Bahls. 2013. *Encyonema hamsherae*, a new species from the Northern Rocky Mountains, USA. Phytotaxa 127(1):58-65. doi: 10.11646/phytotaxa.127.1.9

Wolock, D. M. 2003. Base-flow index grid for the conterminous United States. U.S. Geological Survey open-file report 03-263. U.S.Geological Survey, Lawrence, Kansas.

Wolock, D. M., and G. J. McCabe. 1999. Explaining spatial variability in mean annual runoff in the conterminous United States. Climate Research 11(2):149-159.

Yamada, H., and F. Nakamura. 2002. Effect of sediment deposition and channel works on periphyton biomass in the Makomanai River, Northern Japan. River Research and Applications 18:481-493.

Zavaleta, E. 2000. The economic value of controlling an invasive shrub. Ambio: A Journal of the Human Environment 29:462-467.

Zuur, A. F., E. N. Ieno, and C. S. Elphick. 2010. A protocol for data exploration to avoid common statistical problems. Methods in Ecology and Evolution 1(1):3-14. doi: 10.1111/j.2041-210x. 2009.00001.x.

Appendix A: Sample Sites

Table A1. Glacier National Park Stream Ecological Integrity survey sites and sample events from 2007 to 2009 (partial sample events are in parentheses). U = upper; M = middle, L = lower. *Site was initially selected by the survey design but then also used as a sentinel site.

		Sample events								
Site ID	Stream name	2007	2008	2009	Total	Latitude	Longitude	Stream order	Catchment area (km²)	Elevation (m)
SEI-002	North Fork Flathead River U	–	1(0)	–	**1(0)**	48.874	-114.369	5	2075.8	1134
SEI-003	Belly River U	–	1(0)	–	**1(0)**	48.868	-113.726	4	28.0	1497
SEI-004	Nyack Creek U	–	1(0)	–	**1(0)**	48.544	-113.560	4	62.0	1338
SEI-005	Quartz Creek L	2(0)	2(0)	2(0)	**6(0)**	48.750	-114.184	4	122.8	1171
SEI-006	Starvation Creek	2(0)	2(0)	2(0)	**6(0)**	48.973	-114.357	3	37.5	1339
SEI-007	Mineral Creek	–	2(0)	1(0)	**3(0)**	48.763	-113.821	4	54.5	1180
SEI-008	Lincoln Creek Tributary	–	1(0)	–	**1(0)**	48.535	-113.879	3	11.1	1114
SEI-009	North Fork Flathead River L	–	1(0)	–	**1(0)**	48.652	-114.171	6	3362.6	1034
SEI-010	Boundary Creek	–	1(0)	–	**1(0)**	48.992	-114.018	1	5.1	1548
SEI-011	Hudson Bay Creek	–	1(0)	–	**1(0)**	48.627	-113.522	3	17.1	1535
SEI-012	Middle Fork Flathead River U	–	1(0)	1(0)	**2(0)**	48.320	-113.626	6	1606.1	1110
SEI-013	N. Fork Flathead River G. Rim	0(2)	1(4)	–	**1(6)**	48.485	-114.102	6	4040.3	955
SEI-014	Belly River L	–	2(0)	1(0)	**3(0)**	48.930	-113.715	5	141.8	1423
SEI-015	Appistoki Creek	–	2(0)	2(0)	**4(0)**	48.484	-113.355	2	6.1	1627
SEI-016	Ole Creek U	–	1(0)	–	**1(0)**	48.389	-113.381	3	21.7	1601
SEI-017	Bowman Lake Tributary	1(0)	–	–	**1(0)**	48.832	-114.174	2	3.4	1416
SEI-018	Bowman Creek	1(0)	–	–	**1(0)**	48.800	-114.241	4	132.2	1161
SEI-020	Thompson Creek Tributary	–	1(0)	–	**1(0)**	48.564	-113.628	3	9.7	1268
SEI-023	McDonald Creek U	–	1(0)	–	**1(0)**	48.700	-113.813	5	206.7	1056
SEI-025	Howe Creek	–	1(0)	–	**1(0)**	48.576	-114.007	2	9.6	1103
SEI-027	Red Eagle Creek	–	1(0)	–	**1(0)**	48.667	-113.494	4	93.5	1418
SEI-032	Railroad Creek Tributary	–	1(0)	–	**1(0)**	48.396	-113.255	2	13.4	1496
SEI-033	Waterton River L	–	–	1(0)	**1(0)**	48.863	-113.916	3	29.1	1445
SEI-034	Akokala Creek	1(0)	–	–	**1(0)**	48.852	-114.287	4	70.7	1200
SEI-037	McGee Creek	1(0)	–	–	**1(0)**	48.629	-114.080	3	24.0	1095
SEI-041	Camas Creek M	1(0)	–	–	**1(0)**	48.636	-113.980	3	66.3	1157
SEI-049	Dutch Creek	1(0)	–	–	**1(0)**	48.691	-113.994	2	22.5	1274
SEI-091	South Fork Cut Bank Creek	–	1(0)	–	**1(0)**	48.583	-113.348	1	1.8	1755
SEI-093	Rubideau Creek Tributary	–	1(0)	–	**1(0)**	48.499	-114.018	1	1.4	995
SEI-095	Saint Mary River	–	1(0)	–	**1(0)**	48.662	-113.640	4	59.0	1409
SEI-097	Waterton River U	–	–	1(0)	**1(0)**	48.855	-113.929	3	23.9	1461
SEI-098	Parke Creek	2(0)	2(0)	2(0)	**6(0)**	48.870	-114.264	3	24.1	1289
SEI-100	McDonald Creek L	–	1(0)	–	**1(0)**	48.645	-113.850	5	278.7	996
SEI-101	Camas Creek L	2(0)	2(0)	2(0)	**6(0)**	48.632	-114.106	4	198.6	1054
SEI-104	Middle Fork Flathead River L	–	1(0)	–	**1(0)**	48.372	-113.673	6	1694.7	1092
SEI-105	Camas Creel U	2(0)	2(0)	1(0)	**5(0)**	48.669	-113.926	3	43.6	1194
SEI-108	Nyack Creek L	–	1(0)	–	**1(0)**	48.457	-113.755	4	202.0	1026
SEI-109	Apgar Creek	–	1(0)	–	**1(0)**	48.532	-114.001	3	9.4	978
SEI-129	Quartz Creek U	1(0)	–	–	**1(0)**	48.817	-114.164	4	66.4	1280

Table A1 (continued). Glacier National Park Stream Ecological Integrity survey sites and sample events from 2007 to 2009 (partial sample events are in parentheses). U = upper; M = middle, L = lower. *Site was initially selected by the survey design but then also used as a sentinel site. See also Figure A1.

		Sample events								
Site ID	Stream name	2007	2008	2009	Total	Latitude	Longitude	Stream order	Catchment area (km²)	Elevation (m)
SEI-022*	N. Fork Flathead R. Border	1(0)	2(0)	1(2)	**4(2)**	48.994	-114.466	5	1125.2	1207
SEI-S05	Ole Creek L	–	–	1(1)	**1(1)**	48.795	-113.680	4	21.5	1505
SEI-S01	Swiftcurrent Creek	1(0)	1(0)	1(2)	**3(2)**	48.692	-113.716	3	2.5	1305
SEI-S04	Reynolds Creek	–	1(0)	1(1)	**2(1)**	48.307	-113.484	3	77.6	1984
SEI-G01	Divide Creek	1(0)	1(0)	–	**2(0)**	48.745	-113.432	3	39.1	1380
SEI-G02	Coal Creek	1(0)	–	–	**1(0)**	48.690	-114.197	3	210.5	1043
SEI-G03	Canyon Creek	1(0)	–	–	**1(0)**	48.507	-114.141	6	77.0	977
SEI-G04	Big Creek	1(0)	–	–	**1(0)**	48.603	-114.165	6	214.3	1012
SEI-G06	Fish Creek	–	1(0)	–	**1(0)**	48.547	-113.983	2	42.9	963
SEI-G07	Kennedy Creek	–	1(0)	–	**1(0)**	48.860	-113.550	4	47.6	1622

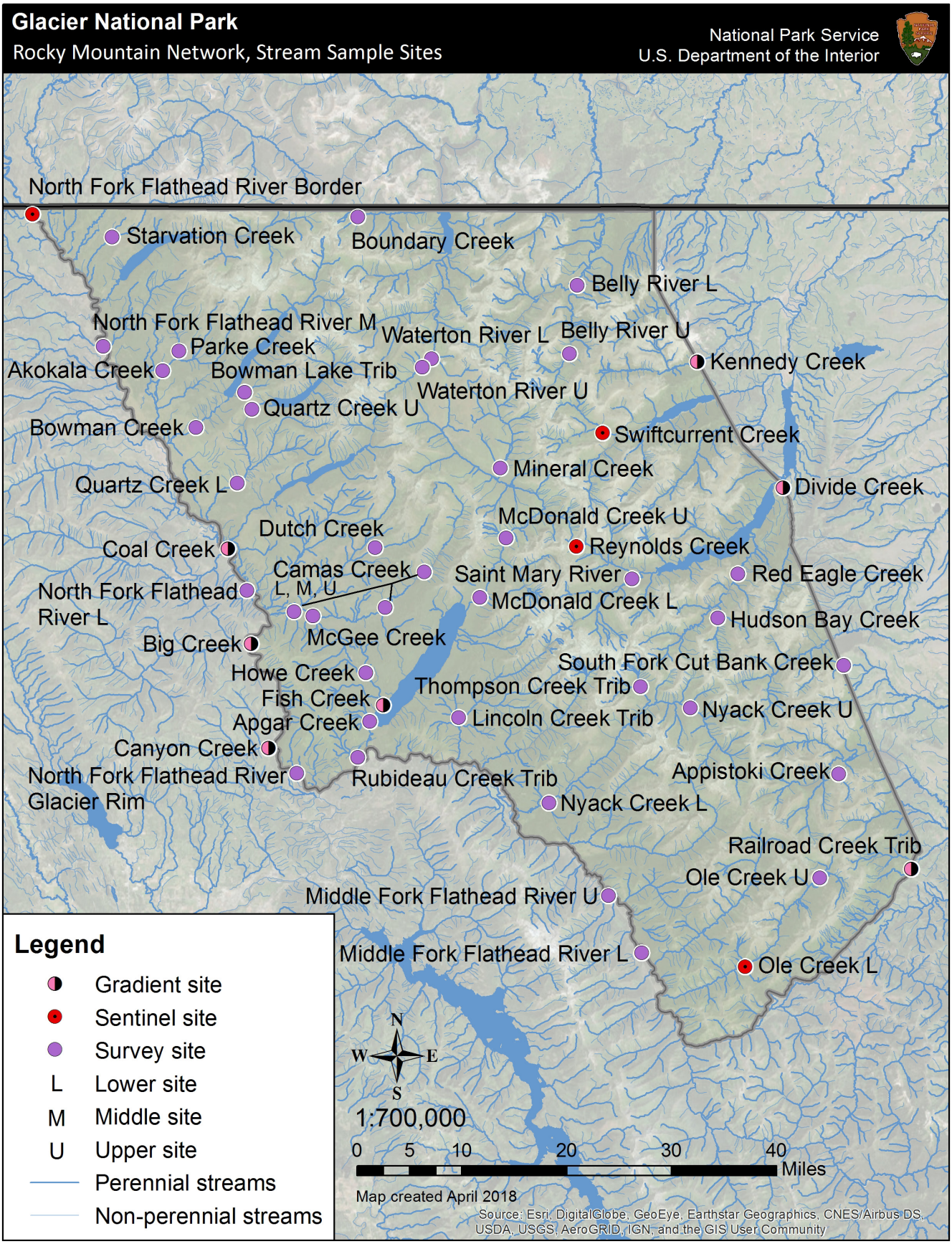


Figure A1. Stream Ecological Integrity monitoring sample sites, Glacier National Park. Note the North Fork of the Flathead Border site is both a survey and sentinel site.

Appendix B: Quality Assurance and Quality Control Overview

For references in this appendix please see the literature cited section that follows the main narrative.

1 Overview

The Rocky Mountain Inventory and Monitoring Network (network) SEI protocol and associated standard operating procedures (SOPs) (Schweiger et al. 2015) include a network Quality Assurance Performance Plan (QAPP) that specifies various Quality Assurance and Quality Control (QAQC) procedures. Table B1 lists the various steps associated with the protocol to ensure data quality and assurance throughout the data lifecycle. All collection and measurement procedures were standardized among all field crews. Field protocols and other activities were documented in peer reviewed SOPs. All field crew personnel participated in a standardized field training session. Field trainers were experienced NPS network staff. Each training session was 1–2 days, and included lectures, field demonstrations, and at least one practice field exercise. The field operations manual served as the basis for the field training program. Field crews often had experienced network staff or collaborators as core members. Field crews were offered an opportunity at the end of each year to suggest improvements to the field operations manual and other aspects of field operations. Systematic errors were minimized by using validated methodologies and standardized procedures. For references in this appendix please see the literature cited section that follows the main narrative.

The network QAPP presents details on Measurement Quality Objectives intended to demonstrate how network monitoring generates data of known and documented quality, resulting in complete, accurate and transferable information. Data credibility necessary for the intended uses will be achieved when data are:

- consistent over time and consistent between staff members
- collected and analyzed using standardized and acceptable techniques
- comparable to data collected in other assessments using the same methods
- used appropriately to make decisions based on sound statistics

The network QAPP also provides a summary of Data Quality Objectives or quantitative and qualitative terms that describe the quality of data needed to meet project objectives. Data Quality Objectives for measurement data (or data quality indicators) are discussed in detail below but are listed by the NPS Water Resources Division as addressing:

- Target population
- Sensitivity
- Representativeness
- Completeness
- Data comparability
- Measurement sensitivity and detection limits
- Measurement precision as repeatability (accuracy)
- Measurement systematic error/bias

All of the various data components of the SEI protocol were managed at the network offices. Completed field forms were reviewed and entered into a database, with several internal QAQC checks. At least 10% of the forms were randomly selected and all data were confirmed. Any systematic errors were evaluated to assess if there was a persistent error with a need for a global correction. Data were reviewed and validated to be sufficiently representative, accurate, precise, and complete.

2 Quality Assurance Quality Control: signal to noise

A key statistic used as part of our QAQC is the ratio of the "signal" to "noise" (S:N) in a response measure (Kaufmann 1999). This is the ratio of variance between multiple sites (signal) and the variance of repeated visits to the same site (noise). Noise includes measurement variation, the combined effects of within-season habitat variation, differences in estimates obtained by separate field crews, uncertainty in the precise relocation of plots, and variation between years. A low S:N value indicates that a metric has nearly as much variability within a site (over time) as it does across different sites, and thus indicates a measure that does not distinguish well between sites. Responses with high S:N values are more likely to show consistent responses to stressors than are metrics with low S:N values. A response that is perfectly correlated with a hypothetical stressor and that has no sampling variability will have an $R^2 = 1.0$ with that stressor. As S:N decreases, the maximum possible R^2 value of the regression decreases because the sampling variability of the metric increases. There is no fixed threshold below which we consider a response poor based on S:N. However, we do use a general rule of thumb from Stoddard et al. (2008) of S:N < 1.0. An

Table B1. Summary of quality control and quality assurance steps for Stream Ecological Integrity monitoring by the Rocky Mountain Inventory and Monitoring Network.

Core QA and QC measure	Description of the action
Documentation	Documentation via protocol, SOPs, methodology, etc., readily accessible.
Training	Pre-season training of field crew.
Field datasheets	Datasheets with standardized codes, precision guidelines for measured values, and clearly documented methodology to complete the form.
Field oversight	Crew leader/protocol lead oversight during the field season and or periodically during data collection.
Field datasheet review	End of the day or end of week quality assurance review of field datasheets for completeness, recording errors, and legible handwriting.
Data entry quality control	Data entry quality control measures, including for electronic data collection devices, to eliminate misspellings, to standardize entry, and reduce errors (drop down menus, value range, limited lists, check boxes, and species lists).
Quality assurance post-data entry	Quality assurance review following SOP DM Quality Assurance and Quality Control Queries are applied to the data post-data-entry to isolate errors. All tests and procedures should be documented in the (draft) SOP SEI: Quality Control and Quality Assurance.
Quality assurance post-analyses	Quality assurance tests for derived data prior to uploading to the database. All tests and procedures should be documented in the (draft) SOP SEI: Quality Control and Quality Assurance.
Quality assurance queries for data recorded by a digital device	Data collected with electronic equipment must undergo tests using QA software, queries in MS Access, or graphical review in MS Excel for outliers and missing data. Assessment points must be developed for accepting or omitting data. All tests and procedures should be documented in the (draft) SOP SEI: Quality Control and Quality Assurance
Lab data quality control	Protocol methodology establishes quality control pertaining to the sample collection. The network assumes contract labs maintain a level of quality control that is trackable internally.
Lab data quality assurance	Chain of custody forms are crosswalked with lab sample results for completeness. Data results are reviewed by the protocol lead for outliers and missing data prior to uploading to the database.
Species lists	At the end of the field season, the species list, with additions from the current year, are crosswalked and updated with code and names as listed in NPSpecies, ITIS, CNHP, Weber, and USDA Plants. Database is updated prior to data entry.

S:N below 1.0 indicates that visiting a single site twice would yield as much response variability as visiting two different sites.

S:N is derived using a general linear model to compare within-year variance among streams (signal) with the variance between repeat visits within the same year (noise). The noise variance includes the combined effects of within-season habitat variation, differences in estimates obtained by separate field crews, and uncertainty in the precise relocation of plots. When describing S:N for the initial sample years in Glacier, we restrict data used in the models to survey sites sampled between 2007 and 2009. We do include within-visit QAQC samples but do not include QAQC samples generated within a lab that have no bearing on the response at an actual stream site (i.e., blanks or spiked samples).

3 Laboratory Quality Assurance and Quality Control

Quality Assurance and Quality Control performed by network contract labs involves specific tasks undertaken to determine the reliability of field and laboratory results. It is accomplished internally by routinely analyzing blanks, duplicates, and spikes in the day-to-day operation of a laboratory, or externally by incorporating field-originated blanks, duplicates, and spikes into the set of the samples collected within the SEI protocol. The general objectives of lab QAQC are to ensure that: (1) the integrity of data generated in a monitoring effort is not compromised by extraneous sources of contamination (blanks), (2) the reported data are favorably comparable to the true values (accuracy), and (3) the results of a sample collection and measurement process (data generated by analytical procedures) are reproducible (precision).

Rigorous QAQC procedures were also applied to algae (diatom) and macroinvertebrate samples. Diatom and macroinvertebrate data accuracy and precision were assured by a blind, quantitative quality-assurance approach, with a minimum of 10% of samples randomly selected for analysis. Bray-Curtis similarity between counts and identification performed independently by two analysts on QAQC samples

was required to exceed 95% (Bray and Curtis 1957). If the required accuracy was not met, the samples were reanalyzed with lessons learned from this applied to all samples. Table B2 presents laboratory detection limits for Glacier chemistry data collected between 2007 and 2009. While the exact definition of a detection limit has varied with lab, the network defines the method detection limit as the lowest level at which the entire analytical system must give a recognizable signal and acceptable calibration point for the analyte (Helsel 2005).

Table B2. Water chemistry method detection limits for Glacier National Park stream monitoring data, 2007–2009. Values are across years and across any within-parameter variation in a detection limit. Dashes in the two righthand columns indicate that values are missing or not applicable. Method details and full citations for indicated methods are found within each lab's respective standard operating procedures, available from the Rocky Mountain Network upon request. Lab codes: FLBS = Flathead Lake Biological Station; Kiowa = University of Colorado Kiowa Lab; EPA = EPA Region 8 laboratory; NRSA = EPA National Rivers and Streams Assessment National Laboratory.

Parameter	Lab	Method	Units	Method detection limit (Min)	Method detection limit (Max)
Alkalinity, Carbonate as CaCO3	FLBS	Standard Methods 2320	mg/l CaCO3	0.849	0.849
Alkalinity, Carbonate as CaCO3	Kiowa	Standard Methods 2320	mg/l CaCO3	–	–
Alkalinity, Carbonate as CaCO3	NRSA	EPA 310.1	mg/l CaCO3	–	–
Aluminum	EPA	EPA 200.7	ug/l	100	100
Aluminum	FLBS	EPA 200.7	ug/l	200	200
Aluminum	NRSA	EPA 200.8	ug/l	–	–
Arsenic	EPA	EPA 200.8	ug/l	4	4
Arsenic	FLBS	EPA 200.7	ug/l	25	25
Barium	EPA	EPA 200.7	ug/l	4	4
Barium	FLBS	EPA 200.7	ug/l	5	5
Beryllium	EPA	EPA 200.7	ug/l	1	1
Beryllium	FLBS	EPA 200.7	ug/l	0.5	0.5
Cadmium	EPA	EPA 200.8	ug/l	0.2	0.2
Calcium	FLBS	EPA 200.7	mg/l	0.1	0.1
Calcium	Kiowa	Kiowa_PerkinElmer200	mg/l	0.005040013	0.005040013
Calcium	NRSA	EPA 215.1	mg/l	0.1	0.1
Carbon, organic	EPA	EPA 415.2	mg/l	0.5	0.5
Carbon, organic	FLBS	Standard Methods 5310-D	mg/l	0.245	0.518
Carbon, organic	Kiowa	Kiowa_ShimadzuTOCV	mg/l	0.093465725	0.093465725
Carbon, organic	NRSA	EPA 415.2	mg/l	0.2	0.2
Chloride	FLBS	EPA 300.1	mg/l	0.251	0.317
Chloride	Kiowa	Kiowa_Metrohm761_IC	mg/l	0.016273798	0.016273798
Chloride	NRSA	EPA 325.1	mg/l	0.2	0.2
Chromium	EPA	EPA 200.7	ug/l	2	2
Chromium	FLBS	EPA 200.7	ug/l	10	10
Color, True	NRSA	EPA 110.2	Su	5	5
Copper	EPA	EPA 200.7	ug/l	10	10
Copper	FLBS	EPA 200.7	ug/l	10	10

Table B2 (continued). Water chemistry method detection limits for Glacier National Park stream monitoring data, 2007–2009. Values are across years and across any within-parameter variation in a detection limit. Dashes in the two righthand columns indicate that values are missing or not applicable. Method details and full citations for indicated methods are found within each lab's respective standard operating procedures, available from the Rocky Mountain Network upon request. Lab codes: FLBS = Flathead Lake Biological Station; Kiowa = University of Colorado Kiowa Lab; EPA = EPA Region 8 laboratory; NRSA = EPA National Rivers and Streams Assessment National Laboratory.

Parameter	Lab	Method	Units	Method detection limit (Min)	Method detection limit (Max)
Fluorides	EPA	EPA 300.0	mg/l	0.2	0.2
Hardness, carbonate	EPA	SM 2340B	mg/l CaCO3	1.3	1.3
Iron	EPA	EPA 200.7	ug/l	100	100
Iron	FLBS	EPA 200.7	ug/l	100	100
Lead	EPA	EPA 200.8	ug/l	1	1
Lead	FLBS	EPA 200.7	ug/l	80	80
Magnesium	FLBS	EPA 200.7	mg/l	0.4	0.4
Magnesium	Kiowa	Kiowa_PerkinElmer200	mg/l	0.002375885	0.002375885
Magnesium	NRSA	EPA 242.1	mg/l	0.1	0.1
Manganese	EPA	EPA 200.7	ug/l	2	2
Manganese	FLBS	EPA 200.7	ug/l	4	4
Manganese	Kiowa	Kiowa_PerkinElmer200	ug/l	1.236449588	1.236449588
Nickel	EPA	EPA 200.7	ug/l	2	2
Nitrogen	FLBS	Standard Methods 4500-N C.	mg N/l	0.00645	0.01147
Nitrogen	Kiowa	Kiowa_ShimadzuTOCV	mg N/l	0.015908377	0.015908377
Nitrogen	NRSA	EPA 353.2	mg/l	0.00002	0.00002
Ammonium	FLBS	EPA 350.1	mg N/l	0.00356	0.00369
Ammonium	Kiowa	Kiowa_BioTekSynergy2	mg N/l	0.006506628	0.006506628
Ammonium	NRSA	EPA 350.1	mg N/l	0.02	0.02
Nitrogen, inorganic	Kiowa	Kiowa_LachatQC8500	mg N/l	0.008746441	0.008746441
Nitrate	Kiowa	Kiowa_Metrohm761_IC	mg N/l	0.001533627	0.001533627
Nitrate	NRSA	EPA 353.2	mg N/l	0.1	0.1
Nitrite + Nitrate	FLBS	EPA 353.2	mg N/l	0.000844	0.001062
Nitrite + Nitrate	Kiowa	Kiowa_LachatQC8500	mg N/l	0.002246441	0.002246441
Nitrite	Kiowa	Kiowa_LachatQC8500	mg N/l	0.001851041	0.001851041
Nitrite	NRSA	EPA 353.2	mg N/l	0.1	0.1
Nitrogen, organic	Kiowa	Kiowa_LachatQC8500	mg N/l	0.0072	0.0072
pH	FLBS	EPA 150.1	su	–	–

Table B2 (continued). Water chemistry method detection limits for Glacier National Park stream monitoring data, 2007–2009. Values are across years and across any within-parameter variation in a detection limit. Dashes in the two righthand columns indicate that values are missing or not applicable. Method details and full citations for indicated methods are found within each lab's respective standard operating procedures, available from the Rocky Mountain Network upon request. Lab codes: FLBS = Flathead Lake Biological Station; Kiowa = University of Colorado Kiowa Lab; EPA = EPA Region 8 laboratory; NRSA = EPA National Rivers and Streams Assessment National Laboratory.

Parameter	Lab	Method	Units	Method detection limit (Min)	Method detection limit (Max)
pH	Kiowa	Kiowa_AccumetAR10	su	–	–
pH	NRSA	EPA 150.6	su	–	–
Phosphorus	FLBS	Standard Methods 4500-P F.	mg P/l	0.000914	0.001557
Phosphorus	Kiowa	Kiowa_LachatQC8500	mg P/l	0.001677202	0.001677202
Phosphorus	NRSA	EPA 365.1	mg/l	0.00002	0.00002
Phosphorus, organic	Kiowa	Kiowa_LachatQC8500	mg P/l	0.0001	0.0001
Phosphorus, orthophosphate	FLBS	EPA 365.2	mg/l	0.000157	0.000157
Phosphorus, orthophosphate	Kiowa	Kiowa_LachatQC8500	mg P/l	0.0016	0.0016
Phosphorus, phosphate	Kiowa	Kiowa_LachatQC8500	mg P/l	0.000618795	0.000618795
Potassium	FLBS	EPA 200.7	mg/l	2	2
Potassium	Kiowa	Kiowa_PerkinElmer200	mg/l	0.004751769	0.004751769
Potassium	NRSA	EPA 258.1	mg/l	0.5	0.5
Selenium	EPA	EPA 200.8	ug/l	1	1
Selenium	FLBS	EPA 200.7	ug/l	80	80
Silicon as Si	Kiowa	Kiowa_LachatQC8500	mg Si/l	0.002354974	0.002354974
Silicon as SiO2	EPA	EPA 200.7	mg SiO2/l	0.2	0.2
Silicon as SiO2	FLBS	Standard Methods 4500-SiO2 C.	mg SiO2/l	0.23	0.23
Silicon as SiO2	Kiowa	Kiowa_LachatQC8500	mg SiO2/l	0.005038031	0.005038031
Silicon as SiO2	NRSA	EPA 370.1	mg SiO2/l	0.5	0.5
Silver	EPA	EPA 200.8	ug/l	0.5	0.5
Sodium	FLBS	EPA 200.7	mg/l	0.8	0.8
Sodium	Kiowa	Kiowa_PerkinElmer200	mg/l	0.00399921	0.00399921
Sodium	NRSA	EPA 273.1	mg/l	0.1	0.1
Total Suspended Sediment (TSS)	EPA	EPA 160.2	mg/l	4	4
Total Suspended Sediment (TSS)	FLBS	Standard Methods 2540-D	mg/l	0.45	0.45
Total Suspended Sediment (TSS)	NRSA	EPA 160.2	mg/l	2	2
Specific conductance	FLBS	Standard Methods 2510	µS/cm	0.5	0.5
Specific conductance	Kiowa	Kiowa_MettlerToledo7	µS/cm	–	–

Table B2 (continued). Water chemistry method detection limits for Glacier National Park stream monitoring data, 2007–2009. Values are across years and across any within-parameter variation in a detection limit. Dashes in the two righthand columns indicate that values are missing or not applicable. Method details and full citations for indicated methods are found within each lab's respective standard operating procedures, available from the Rocky Mountain Network upon request. Lab codes: FLBS = Flathead Lake Biological Station; Kiowa = University of Colorado Kiowa Lab; EPA = EPA Region 8 laboratory; NRSA = EPA National Rivers and Streams Assessment National Laboratory.

Parameter	Lab	Method	Units	Method detection limit (Min)	Method detection limit (Max)
Specific conductance	NRSA	9050A	µS/cm	2	2
Sulfur, sulfate as S	Kiowa	Kiowa_Metrohm761_IC	mg S/l	0.001121523	0.001121523
Sulfur, sulfate as SO4	FLBS	EPA 300.1	mg SO4/l	0.13	0.308
Sulfur, sulfate as SO4	Kiowa	Kiowa_Metrohm761_IC	mg SO4/l	0.003360008	0.003360008
Sulfur, sulfate as SO4	NRSA	EPA 375.2	mg SO4/l	2.5	2.5
Turbidity	FLBS	Standard Methods 2130	NTU	0.297	0.297
Turbidity	NRSA	EPA 180.1	NTU	2	2
Zinc	EPA	EPA 200.7	ug/l	40	40
Zinc	FLBS	EPA 200.7	ug/l	4	4

Appendix C: Auxiliary Data

For references in this appendix please see the literature cited section that follows the main narrative.

Several types of auxiliary data were used in analyses of Glacier SEI data. These data were pulled from readily available NPS or partner sources and built into the SEI database. Brief descriptions by major class are given below. For references in this appendix please see the literature cited section that follows the main narrative.

1 Climate

Hansen et al. (2014) and Colwell et al. (2012) suggest understanding changing climatic conditions should be incoporated in how parks like Glacier are managed into the future. As our data are intended to help in the management of Glacier's stream resources, we include climate in our analyses of SEI monitoring data. Future work will continue to enhance this effort.

We use climate data from ~800-m grid cells from the Parameter-elevation Relationships on Independent Slopes Model (PRISM, PRISM Climate Group 2017; Daly et al. 2008). PRISM data are derived using an interpolation method that reflects the current state of knowledge of spatial climate patterns. A climate–elevation regression for each digital cell is generated from nearby climate station data that incorporates location, elevation, coastal proximity, topographic orientation, vertical atmospheric layer, topographic position, and orographic effectiveness of the terrain into how station data are assigned to each data point over time. Monthly temperature and precipitation were obtained for all SEI points from 1980 to 2010 PRISM data.

We also use data from select National Weather Service stations (East Glacier ID #: 242629 and West Glacier ID #: 248809) to summarize representative patterns over time. PRISM data have the advantage of reflecting variation in climate due to space.

We used various metrics to characterize patterns in precipitation and temperature, including sums or means across weather station data at a site or over a site's catchment using PRISM values for a given time interval.

2 Water temperature

We use modeled stream water temperate data from Isaak et al. (2016). We summarized (mean, minimum, maximum) predicted stream temperatures by year of sample across all stream reaches in each site's catchment (Figure C1).

Predicted data were generated by the NorWest program ("North West"; Isaak et al. 2016) which is a multiagency effort lead by the US Forest Service – the NPS is also an active participant in the project. Twelve predictor variables were used to model August stream temperatures for a given year (Table C1). The predictors represented the spatial characteristics of a river network that affected stream temperatures within an individual year. Stream temperature observations used in the model came from multiple sources (including the network for several Glacier SEI sites). To address issues with autocorrelation and parameter estimate bias, spatial statistical models for stream networks were used (Ver Hoef et al. 2006; Ver Hoef and Peterson 2010; Peterson et al. 2013). These models account for the unique forms of spatial dependence that occur on stream networks (e.g., longitudinal connectivity, flow-volume, and flow-direction; Peterson and Ver Hoef 2010) and have provided accurate temperature predictions when used with similar stream temperature databases previously (Isaak et al. 2010; Isaak et al. 2014). After the spatial statistical models were fit to the temperature database within a river basin, the model was used to make predictions representing climate scenarios at 1 kilometer intervals throughout the river network. Climate scenarios for historical conditions were created by setting mean August air temperature and stream discharge values to match those observed for a historical period, whether it was an individual year or a composite of multiple years (e.g., 1993–2011).

3 Runoff

Runoff is defined as the amount of water flowing overland per unit time. We summarized runoff as a total value across all grid cells in each site's catchment (Figure C2).

Runoff accumulates in streams, lakes and groundwater as it moves through a basin. Runoff is extremely important because not only does it keep rivers and lakes full of water, but it also changes the landscape by the action of erosion. We use estimates of runoff from Wolock and McCabe (1999). These are derived from a water-balance model that estimates the spatial variation in mean annual runoff for 344 climate divisions in the conterminous United States at a 1 km scale. Components of the model include climatic supply of water (precipitation), climatic demand for water (potential evapotranspiration), seasonality in supply and demand, and soil moisture storage capacity. Most (91%) of the spatial variability in mean annual runoff for the climate divisions in the conterminous United States is explained by the spatial variability of mean annual precipitation minus mean annual potential evapotranspiration. Adding soil moisture storage capacity and seasonality in supply and demand provided

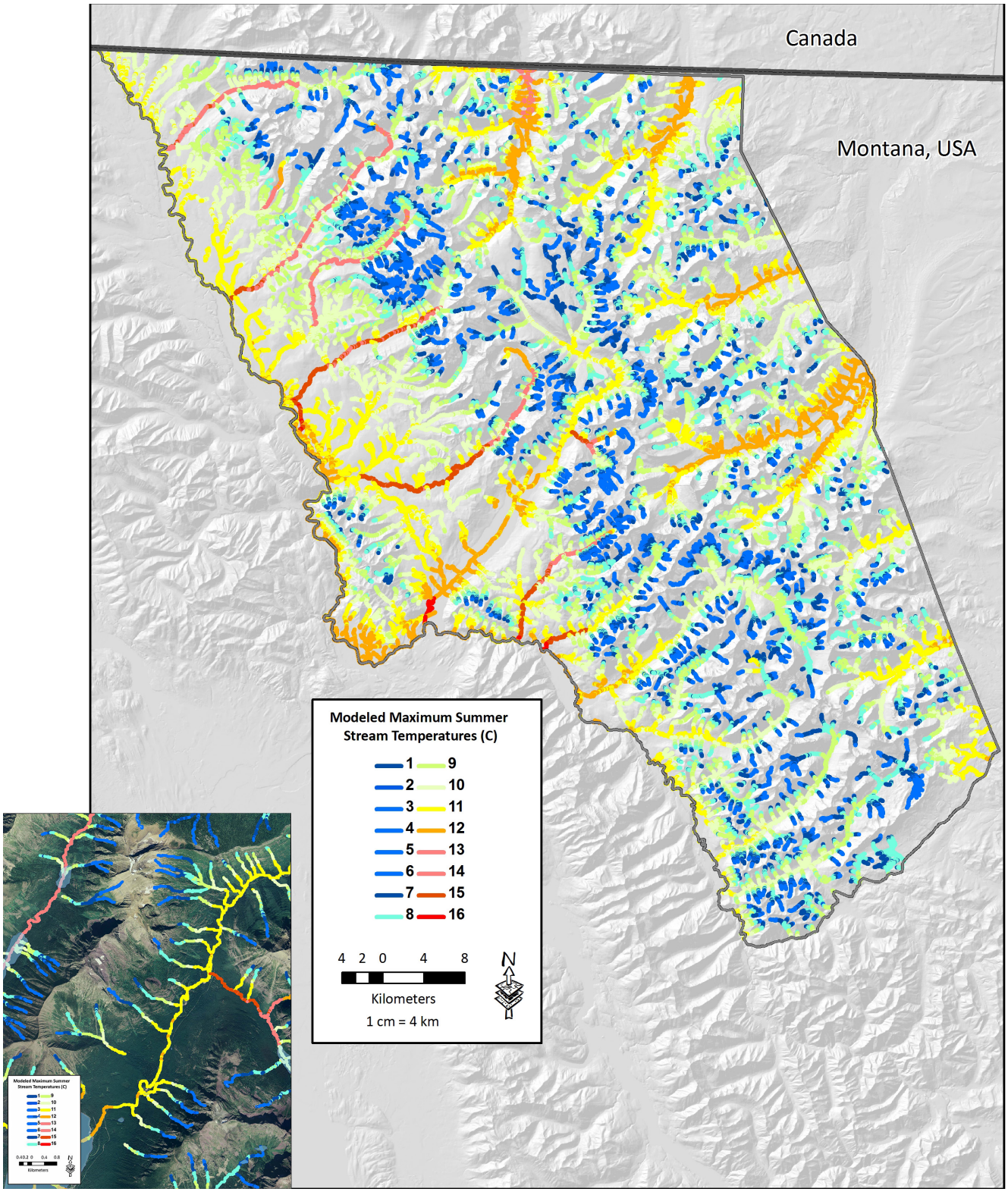


Figure C1. Predicted stream temperatures in Glacier National Park, August 2008 model (Isaak et al. (2016). Inset shows details of spatial patterning in stream temperature within the Belly River area in the Northeast corner of the park and uses the same legend color scheme as the larger map. Redder colors indicate hotter stream water temperatures.

Table C1. Predictor variables in the NorWest stream temperature model (Isaak et al. 2016).

Predictor	Description	Use/justification
Air temperature in August (°C)	Mean August air temperature for a river basin derived from a dynamically downscaled re-analysis (Hostetler et al. 2011)	key driver of water temperature
Stream discharge in August (m^3/s)	Mean August stream discharge for a river basin derived by averaging across USGS flow gages with long-term records	key driver of water temperature
Elevation (m)	Elevation at stream temperature sites was used to represent the vertical trend towards cooler air temperatures and stream water. Data were obtained from the 30-m resolution National Elevation Dataset	represents the vertical trend towards cooler air temperatures and groundwater
Latitude (m)	The y-coordinate at stream temperature sites from the Albers Equal Area projection was used to represent the poleward trend towards cooler air temperatures	represents the poleward trend towards cooler air temperatures
Canopy %	The percent tree canopy from the 2001 National Land Cover Database (Homer et al. 2007)	Represents stream shade near a temperature site
Cumulative drainage area (km^2)	The accumulated drainage area value in National Hydrography Dataset at a stream temperature site was used to represent stream size and amount of insolation (McKay et al. 2014)	larger watersheds assumed to have larger streams that had been insolated over greater distances and would be less shaded by adjacent riparian vegetation due to their greater width
Stream slope %	The stream channel gradient value from National Hydrography Dataset	steeper slopes, therefore, should negatively affect stream temperatures because conditions further upstream at higher elevations have greater influence on local temperatures
Mean annual precipitation (mm)	The mean annual precipitation averaged over the area of each site's catchment (McKay et al. 2014)	areas with high annual precipitation may produce higher water yields that have a cooling effect on streams
Base flow index	The value of the base flow index from Wolock (2003). Base flow is the component of stream flow that can be attributed to groundwater discharge into streams. The index is the ratio of base flow to total flow, expressed as a percentage.	streams with larger base flows and groundwater contributions that are thought to be colder than other streams and potentially less sensitive to climate warming
Glacier %	The percentage of the upstream catchment area classified as glacier (Fountain et al. 2006) at each temperature site. Summaries were computed using a standard flow accumulation routine in a GIS.	represents the local cooling effect that glaciers may have on downstream temperature
Lake %	The value of accumulated open water from the National Land Cover Database (McKay et al. 2014),	represents the percentage of the catchment area classified as open water at a temperature site and the warming effect that natural lakes and many reservoirs have on downstream temperatures
Tailwater	Categorical predictor variable	indicates whether a stream temperature site occurred in a reach downstream of a deep reservoir that is anomalously cold due to releases of hypolimnetic waters

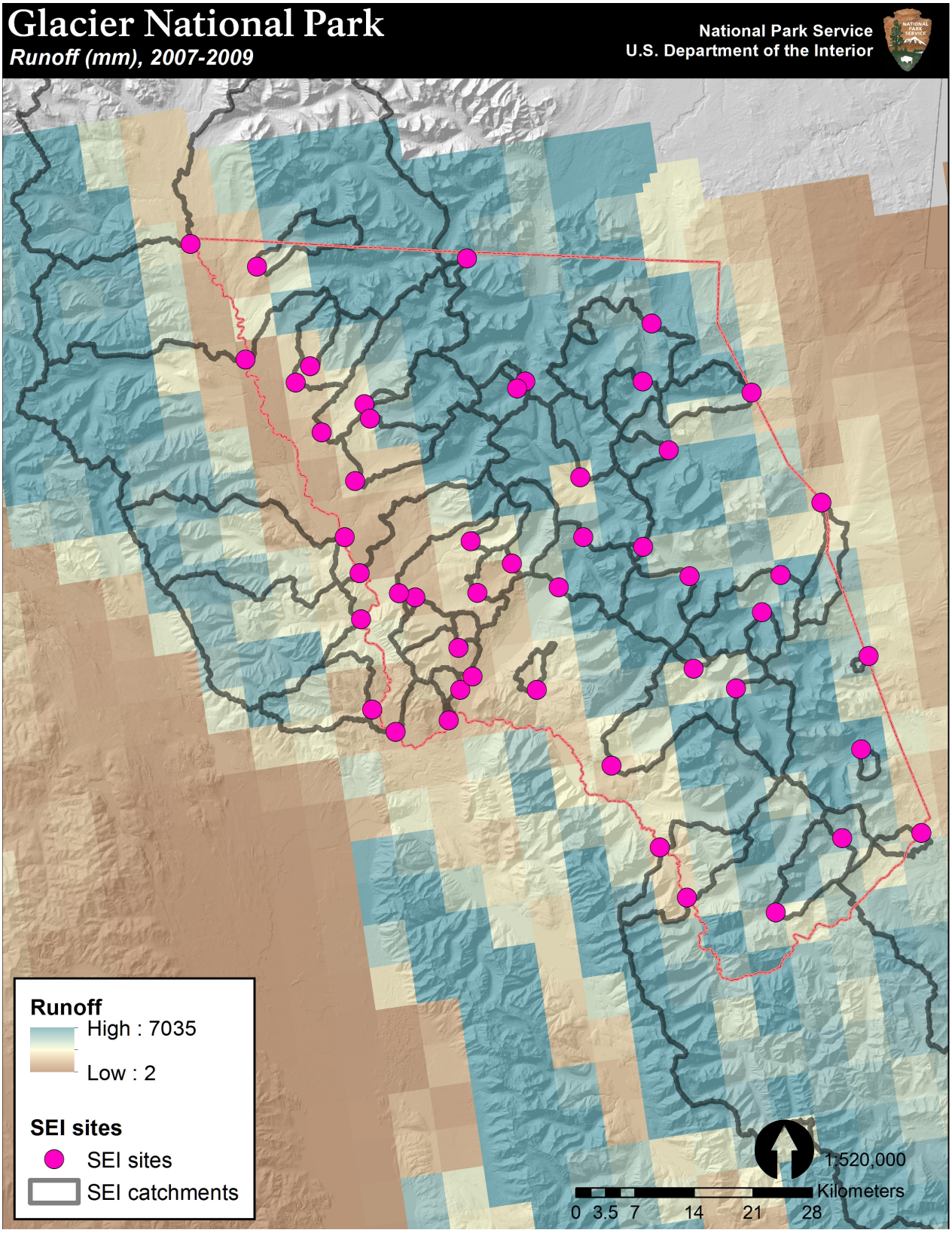


Figure C2. Runoff (mm) grid (Wolock and McCabe 1999) at Glacier National Park showing catchments and Rocky Mountain Network Stream Ecological Integrity monitoring sites. Bluer colors indicate higher runoff values. The full extent of catchments to the North and South of the park is not shown. See Appendix A for a complete list of site numbers and names.

the most improvement in areas where seasonal supply and demand are out of phase.

4 Landscape composition: geophysical attributes and disturbances

Similar to the impacts of climate on park resources, the composition of landscapes in and around parks matters greatly to park resource management (Hansen et al. 2014). Intensification of anthropogenic land use leads to the conversion of natural habitat and fragmentation of remaining natural areas in and around parks. It can also increase edge zones, reduce core areas, and change runoff of water, sediments, and nutrients (Monahan and Gross 2012).

We use a variety of landscape data sources. Most important perhaps is a vegetation map (Hop et al. 2007) produced from 1997 to 1999, using 1:42,000-scale color infrared aerial photography, and ground-truthing from over 800 points, to interpret the complex patterns of vegetation and land use at Glacier. While most map unit types in the vegetation map were natural, several anthropogenic land use types were included. The vegetation map has a final accuracy of 87.4% (estimated from 918 accuracy assessment points) and a minimum mapping unit of 0.5 ha that provided high resolution to resolve spatial patterns.

Another important data source was the National Land Cover Database (NLCD; Fry et al. 2011, Homer et al. 2015). These data are the definitive Landsat-based, 30-meter resolution, land cover database for the nation. NLCD provides spatial reference and descriptive data for characteristics of the land surface, such as thematic class (for example, urban, agriculture, and forest), percent impervious surface, and percent tree canopy cover. We used NLCD data where the vegetation map was unavailable. All types were crosswalked between the vegetation map and NLCD to a common map unit.

In many analyses we use data from the National Hydrography Database (NHD; USGS 2017a). NHD data have received additional attention in parks like Glacier, with enhanced resolution and accuracy (R. Menicke, NPS, pers. comm.). We generate stream extent, stream slope, and use the data to estimate distance to lakes from each SEI site along the stream channel. We also calculate a metric of stream size or position within the drainage network following Strahler (1952, 1957) using NHD data.

Several point specific data layers were obtained from the park (R. Menicke, NPS). These included high resolution roads and trails layers, glacier extent, fire bounadaries, and a detailed structures layer. Most of these layers were created from heads up digitizing of imagery or from ground truthed GPS data. Details on these data are available upon request. We used the Analytical Tools Interface for Landscape Assessments (ATtILA; Ebert and Wade 2000, Riitters et al. 2000) modeling package for a road–stream crossing metric. Many landscape and climate variables were summarized over catchments delineated for each site using National Elevation Data (3; USGS 2017a).

5 Biology, habitat, and water chemistry from state/federal ecoregion sites

We collected data for a subset of biological, habitat, and water chemistry responses from partner monitoring sites located in the Northern and Canadian Rockies Ecoregions (see Figure 8, main narrative). The network works with partners who collect comparable auxiliary data, including Montana DEQ, EPA/its partners, and USGS, with most sites part of long-term monitoring conducted by these agencies (Hawkins et al. 2003; Stoddard et al. 2005; Suplee et al. 2005; Bollman 2006). Auxiliary data were typically sampled during different years than SEI data collection in Glacier, and this is an important caveat on models that use these data. The EPA NRSA (National Rivers and Streams Assessment) program (EPA 2007) will be an important future source for additional and more recent data, as field and analytical methods for these programs are largely comparable to the SEI protocol

5.1 Macroinvertebrates

For macroinvertebrates, auxiliary data had appropriate QAQC, a multihabitat sampling method (i.e., not just riffles), a minimum 300 organism lab count, and identical or comparable OTU (operational taxonomic unit) level identification of macroinvertebrates (including midges). Even within these constraints, some data we used come from protocols that differ from the SEI protocol. However, Jessup et al. (2006) show that, for at least MMI (multimetric index) and RIVPACS (River Invertebrate Prediction and Classification) metrics, bioassessment using data collected with Montana DEQ or EPA (on which the SEI protocol is based) methods generates similar interpretation. We restrict sites from which we pull macroinvertebrate data to the state of Montana, given our use of thresholds from Montana DEQ developed from data only from within the state's boundaries. For macroinvertebrates we included 16 sites (10 reference and 6 test) sampled as part of the EMAP (Environmental Monitoring and Assessment Program) Western Pilot Project (Stoddard et al. 2005) from 2000 to 2004, 12 sites in larger rivers (3 degraded, 1 reference, and 8 test) sampled by Montana DEQ from 2001 to 2005 (Bollman 2006), 39 (all reference) sampled by the state

as part of a recent reference condition development process (Suplee et al. 2005), and 28 sites (1 degraded, 13 reference, and 14 test) sampled from 2000 to 2003 by Utah State University as part of the EPA Science to Achieve Results (STAR) program (Hawkins et al. 2003). Five of the sites are treated in multiple sources (i.e., a few EMAP sites became Montana DEQ reference sites), reducing the total unique site sample size. Specific sample sizes used in analyses include select repeat events at some of these sites (we assume that events in different water years at the same site are independent and can be used as unique data points). Finally, the number of data points for a given metric varied (due to missing data, etc.) and final sample sizes are given with each treatment in the results section below.

5.2 Diatoms

At the time of this report's publication, we had yet to acquire auxiliary algae data. When we do it will have appropriate QAQC, a multihabitat sampling method (i.e., depositional and erosional habitats), a Palmer-Maloney or similar counting chamber count of 300 soft-bodied algae cells, and a proportional count of 600 diatom valves (300 cells). Most importantly, specimens will be identified to species as often as possible. Nomenclature will follow the Montana Diatom Database (Bahls 2004) as there is not well developed taxonomic data in ITIS (Integrated Taxonomic Information System) or NPSpecies (the National Park Service online biodiversity database) for algae. We may restrict sites from which we pull algae data to the state of Montana, given that we will probably use thresholds from Montana DEQ.

5.3 Water chemistry

For water chemistry, auxiliary data should have appropriate QAQC, a depth integrated thalweg sampling method, and published detection limits that are sufficiently precise enough for the often dilute waters in network parks. For water chemistry data, we include 51 sites (27 reference and 24 test).

5.4 Habitat

For habitat, we restricted auxiliary data to sites sampled as part of the EPA EMAP Western Pilot Project (Stoddard et al. 2005) or (in the future) from NRSA, given near identical field and analytical methods with the SEI protocol. We do not restrict habitat data to the state of Montana because there are no Montana DEQ thresholds for habitat responses and we either develop our own thresholds or use existing values created for an entire ecoregion. For habitat data we include 51 sites (27 reference and 24 test) sampled as part of the EMAP Western Pilot Project (Stoddard et al. 2005) from 2000 to 2004.

Appendix D: Assessment Methods and Analysis Details

The following sections present summaries of how Glacier data were analyzed and interpreted. We present general overviews of analytical strategies in Schweiger et al. (2015). However, because this report is the first time we have detailed our modeling, there is more content here. We group the narrative by the general type of analysis rather than the order of objectives, but do link each analysis back to the relevant motivating objective. For references in this appendix please see the literature cited section that follows the main narrative.

Note for sites with replicates across 2007–2009, most analyses use the sample event where macroinvertebrate taxa were most developed, the crew consisted of the best trained technicians, and stream discharge was at its lowest (thus aquatic biota most stressed). These events may sometimes be referred to in this document as the "best" sample event. Replicate events at sites may be used in select analyses such as power models, estimates of precision, and as test data for bioassessment models.

All code is available upon request from the network and will appear in a future revision of the SEI protocol as detailed SOPs.

1 Assessment details

1.1 Water chemistry

Water chemistry, perhaps more than any other type of response, has the benefit of a spectrum of existing assessment points developed by Montana DEQ, EPA and others for a variety of circumstances. In general we follow this hierarchy: 1) Glacier management derived assessment points (which may include any of the following), 2) state/federal/tribal nation regulatory criteria, 3) ecological thresholds, and 4) "ecoregion" assessment points derived from reference site data within and around Glacier. We provide an overview below.

1.1.1 Glacier management derived assessment points

To date, there are no explicit or unique-to-Glacier management derived assessment points for water chemistry. However, we suggest that Glacier management could adopt some or all of the existing assessment points listed below as useful for the park's management of its stream resources.

1.1.2 Regulatory criteria

There are multiple regulatory criteria used by the Montana DEQ or the EPA and many of these are used here as assessment point(s). From a resource-conservation standpoint, instantaneous grab-sample data like what we collect is best compared against aquatic-life chronic criteria (Montana DEQ 2002, 2012b, 2017) and this is our default. Note that by definition, we classify aquatic-life chronic criteria as bounding a major disturbance classes (i.e., any response value in Glacier above a regulatory criteria is a major stressor) and any value below as a minor stressor. If multiple thresholds exist we assign the intermediate label, moderate, accordingly.

Montana DEQ (2017) also provides "support criteria" for a few parameters that are used in combination with nutrient concentrations and their aquatic-life chronic criteria. Because the possibility of human health issues is rare in the park and aquatic-life chronic criteria are more conservative, we do not include human health criteria (EPA 2002). Similarly, "secondary" criteria provided by the EPA (2017) for some parameters as guidelines to assist public water systems in managing their drinking water for aesthetic considerations, such as taste, color, and odor are not relevant to ecological monitoring and assessment.

Finally, because Glacier waters are designated outstanding resource waters by Montana DEQ, their non-degradation standards apply (Montana DEQ 2017). These are values used to determine if a given change (i.e., from a new point source emitting a pollutant) in the concentration of a parameter is a significant or non-significant "trigger" that could cause Montana DEQ to apply the non-degradation rule (ARM 17.30.701). These trigger values do not specifically apply to our survey monitoring data and its assessment given the lack of point sources at our sites. We include them in our report as they indicate how small a change would be allowed in a parameter within the parks pristine waters under Montana DEQ or EPA's regulatory authority.

1.1.3 Ecological thresholds

There are a few relevant ecological thresholds for water chemistry parameters in Glacier that we utilize. These are generally for *in situ* parameters like dissolved oxygen and are more relevant to continuous data such as presented in the companion sentinel site report to this document (Schweiger et al. in preparation a). Some regulatory criteria also have a basis in an ecological response, especially nutrient criteria developed by the state of Montana (Montana DEQ 2011; Suplee and Sada de Suplee 2011, Suplee and Watson 2013). In cases where there is only one threshold along a gradient we label any value above the threshold value as a major stress and any value below as minor (we use the moderate class as needed).

1.1.4 Ecoregional assessment points

We employ the ecoregional assessment point strategy as presented in the previous section for select parameters. We again largely follow Stoddard et al. (2008) and make the assumption that Glacier is nested in a minimally disturbed condition (MDC) near-pristine landscape. We used both 45 *a priori* reference SEI sites in Glacier (following Montana DEQ (Suplee et al. 2005)) and 32 reference sites within the Northern and Canadian Rockies Ecoregions as sampled by federal and state partners (see Auxiliary data section). For parameters that increase with disturbance, we set baseline MDC assessment points at the 75th and 95th percentiles. Values between the 75th and 95th percentile fall within a moderate disturbance class. Those above the 95th are classed as a major disturbance. Values below the 75th percentile are in a minor disturbance class. Note that there is no equivalent to a negligible or "zero" class for water chemistry as it's not possible to know when or if there is a complete lack of a parameter in a sample (i.e., there is no "zero" point) and we cannot assume that a non-detected value is the same as zero. Importantly, our use of ecoregion assessments points depend on the assumption that there is a linear response in ecological condition to (usually) increasing concentration. In other words we assume that a higher concentration of a parameter leads to greater stress and degraded or non-reference ecological condition.

1.2 Physical habitat

To assess our physical habitat results, we follow the same hierarchy as for water chemistry, above (see also assessment section 2.4.4.2 in the main narrative), with any details specific to habitat metrics clarified below.

1.2.1 Glacier management derived assessment points

To date there are no explicit or unique Glacier management-derived assessment points for physical habitat, and there are no explicit habitat regulatory criteria from Montana DEQ or the EPA (Cantilli et al. 2006). Therefore, we do not assess any habitat response in this context. However, we expect Glacier management would adopt many of the existing assessment points listed below as useful for the park's management of its stream resources. Kusnierz et al. (2013) does present a useful Montana DEQ protocol for evaluating several habitat metrics related to sediment. It is similar to our ecoregion assessment point approach and provides useful support and context for these methods. However this method does not provide thresholds or criteria, requires a protocol that differs in some ways from ours, and is also more regulatory in its application. Therefore we do not apply it to SEI habitat data. Should applicable regulatory criteria be developed, we will review their application in future reports.

1.2.2 Ecological thresholds

There are relevant ecological thresholds for physical habitat that we believe are useful for NPS management. These are mostly based on the biological response of taxa or groups of taxa that occur in Glacier to a specific habitat attribute that is outside of its natural range. We must make some assumptions about the applicability of these thresholds given local variation in species response (Al-Chokhachy et al. 2010). As discussed in the main assessment section above, in most cases where there is only one threshold defined along a gradient, we label any value beyond the threshold value as in a major disturbance class and any value below as a minor disturbance, even if there appears to be negligible or no disturbance at the site . It is difficult to assume negligible disturbance where a metric cannot logically or ecologically have a zero value or we cannot measure the response with this level of precision. This is more a limitation in the need to have categorical, consistently applied disturbance class labels than a reflection of a habitat response in Glacier not being in a low stress disturbance class.

1.2.3 Ecoregional assessment points

Finally, we employ the ecoregional assessment point strategy overviewed in section 2.4.4.2 of the main narrative. We again largely follow Stoddard et al. (2008) and make the assumption that Glacier is nested in a minimally disturbed condition (MDC) landscape. We used both 45 *a priori* reference SEI sites in Glacier (following Montana DEQ (Suplee et al. 2005)) and 75 reference sites within the Northern and Canadian Rockies Ecoregions as sampled by federal and state partners from 2004 to 2008 (see Appendix C) to develop ecoregional assessment points. We set major, moderate, and minor disturbance class assessment points using percentiles set by EPA as defined in the assessment section 2.4.4. With one exception (invasive/exotic plants), there is no equivalent to a negligible or "zero" class for physical habitat metrics. We assume that responses are linearly correlated with ecological condition and human disturbance. Ecoregional assessment points are best treated as baseline context for assessing Glacier SEI results – additional work is needed to further interpret patterns in a specific response.

1.3 Biological response

The assessment of biological data from stream monitoring has a rich history – even its own name "bioassessment."

Bioassessment is, generally speaking, the use of measures of the biological community to assess and monitor natural systems (Barbour et al. 2000) and is the primary way we address objectives focused on estimating status in the condition (or ecology integrity) of Glacier's streams. The process we use for bioassessment follows the same hierarchy as for water chemistry and physical habitat described above (see also assessment section 2.4.4.2 in the main narrative), with any details specific to biological metrics clarified below.

1.3.1 Glacier management derived assessment points

To date there are no explicit or unique Glacier management derived assessment points for biological metrics. However, we expect Glacier management would adopt many of the existing assessment points listed below as useful for the park's management of its stream resources.

1.3.2 Regulatory criteria

There are a few regulatory criteria used by the Montana DEQ for biological data and we apply these to SEI data as appropriate (Montana DEQ 2002, 2012b, 2017). These are used by Montana DEQ in support for assessments using other responses, such as water chemistry. Moreover Montana DEQ biological metrics (or the models used to estimate them) have mixed applicability to the streams of Glacier – we therefore apply these criteria with caution.

1.3.3 Ecological thresholds

There are a few relevant ecological thresholds for biological metrics and we employ these as warranted. These are mostly based on the biological response of taxa or groups of taxa that occur in Glacier to specific stressors.

1.3.4 Ecoregional assessment points

We employ the ecoregional assessment point strategy overviewed in section 2.4.4.2 of the main narrative. We again largely follow Stoddard et al. (2008) and make the assumption that Glacier is nested in a minimally disturbed condition (MDC) landscape. We used both 45 *a priori reference* SEI sites in Glacier (classified following Montana DEQ (Suplee et al. 2005)) and 97 reference sites within the Northern and Canadian Rockies Ecoregions as sampled by federal and state partners (see Appendix C). We classify major, moderate, and minor disturbance classes as defined in section 2.4.4 of the main narrative. In addition, for our park specific MMI, we use predicted MMI values from ecoregional assessment HDI points at major, moderate, and minor disturbance levels as well as a negligible or "zero" class at HDI = 0. Note that ecoregional reference sites for all metrics except our park specific MMI include SEI sites classified using Montana DEQ methods as in an expected reference or minor disturbance class. For all ecoregional assessment points, we assume that responses are linearly correlated with ecological condition and human disturbance. With the exception of the HDI = 0 based value (for which we assign a real ecological interpretation), ecoregional assessment points are best treated as baseline context for assessing Glacier SEI results – additional work is needed to further interpret patterns in a specific response.

2 Site scale status

2.1 Model based descriptive statistics

Objective four (determine the status for select sites in a suite of response measures) requires analyses that estimate the status of select stream responses at site scales. We use traditional or model-based analyses that summarize data as means and various measures of the variance around a mean. Results are presented in simple tables and a variety of figures. In some cases, tabular results are grouped by important factors like stream type or sample design. Importantly, model-based results, including both simple descriptive statistics as well as more complex predictive models, apply only to the sites included in an analysis.

2.2 Understanding status: linear models and the relative importance of predictors

Objective six (relate spatial and temporal patterns in select stream responses to important ecological and anthropogenic drivers) requires analyses that facilitate understanding ecological and statistical connections among SEI responses, drivers of stream condition, and important covariates that influence these patterns. As part of our approach here, we construct linear models that quantify relationships between stream response and important attributes of streams that may predict and thus help explain or interpret patterns in the response. We include a suite of environmental covariates in the models that may influence or covary with the response, thereby statistically controlling for these effects. We use the best events from 2007 to 2009 from survey, gradient, and sentinel sites. Model results do not have any statistical inferential capacity beyond the sites included in them. We limit the responses investigated and reported on those that we hope have the most utility for stream resource management at Glacier or that may support successive bioassessment. Therefore not all SEI responses are modeled in this report.

Models were built using the lm() function within the stats

library in R version 3.2.3 (Chambers 1992; R Development Team 2014). We attempted to keep these models as simple as possible – all terms were treated as fixed and we include no interactions amongst predictors. We chose candidate independent variables for each model using a series of steps. First we used an *a priori* selection based on 1) the inclusion of interpretable variables from across the classes of responses measured in SEI monitoring, and 2) variables that were not confounded with one another based on checks for multicollinearity. We then conducted forwards and backwards stepwise selection based on Akaike Information Criterion (AIC) values using the R library MASS and the stepAIC() function (Venables and Ripley 2002). Final models were constructed by hand based on the stepwise output followed by additional rounds of expert opinion for culling or re-including predictors based on a variable's interpretation, its p-values, and the AIC value of the candidate model. While stepwise procedures have been criticized (i.e., Zuur et al. 2010), and our approach is not entirely automated, we feel that the use of AIC and our interpretation of the ecological relationships among a response and candidate predictors is justified. All variables were first examined as to whether they met the assumptions of parametric models and transformed as needed.

To assist in the interpretation of the final model we estimated the relative contributions of each of the predictors to a model's total explanatory value. We used a classic (but recently much improved; Grömping 2006) approach implemented within the R library relaimpo of averaging sequential sums of squares over orderings of regressors (Lindeman et al. 1980; Kruskall 1987). This produces estimates of each predictor's importance relative to the total amount of explained variance expressed as a simple percentage. These estimates consider both direct effects (i.e., correlations with the response) and its effect when combined with the other variables in the regression equation. Furthermore, the method averages over all possible orderings of predictors in a model, thereby dealing with multicollinearity (Grömping 2006).

We use conditional plots of partial residuals to visualize these models (Larsen and McCleary 1972; Breheny and Burchett 2013). A partial residual plot is a graphical technique that attempts to show the relationship between a given independent variable and the response variable given that other independent variables are also in the model. The plot shows the value of the variable on the x-axis and the change in response on the y-axis, holding all other variables constant (by default, median for numeric variables and most common category for factors).

2.3 Understanding status: clustering and ordination of macroinvertebrate and diatom communities

To further address objectives four (determine the status for select sites in a suite of response measures) and six (relate spatial and temporal patterns in select stream responses to important ecological and anthropogenic drivers) for macroinvertebrate and diatom communities, we use exploratory and descriptive multivariate classification and ordination techniques. These models examine relationships between community composition patterns and the underlying environmental gradients which might be influencing these patterns. They support interpretation of how macroinvertebrate and diatom communities are structured relative to environmental gradients or anthropogenic disturbance and are very useful as setup to successive bioassessment models. We use the best events from 2007 to 2009 from survey, gradient, and sentinel sites and do not statistically infer results to unsampled sites. Our ordinations are an analysis of status with no explicit incorporation of time – future work may include temporal ordinations.

We first removed all unknown taxa from the matrices (we retain all unique but non-species level identifications). Cluster analysis and ordination (but not the diversity estimates above) used datasets where species that occurred in less than 5% of sampled sites were first removed. Removing rare taxa reduces the role of uncommon taxa in having a disproportionate influence on the final configuration (McCune and Grace 2002). Finally, we transformed all count data using the *decostand* log method within the R *vegan* library, as suggested by Anderson et al. (2006).

We examined natural classification variables like stream order and watershed to group assemblage data, but none provided interpretable groupings. We therefore used clustering methods to assign sites to groups based on similarities in the macroinvertebrate or diatom community sampled at each site. *Agnes* clustering using a Sorensen (Bray-Curtis) pair-wise dissimilarity matrix created four distinct macroinvertebrate groups.

We conducted Principal Coordinates Analysis (PCoA) to summarize the community structure within the macroinvertebrate and diatom communities and to begin understanding in a more structural way patterns with key environmental gradients. PCoA maximizes the linear correlation between each sample in a space of low dimension (typically, 2 or 3 axes are selected). An ordination technique other than nonmetric multidimensional scaling (NMDS) was possible

because an adjustment from De'ath (1999) that we applied provides a reasonable solution for samples with a zero-truncation problem. All analyses were done in the R libraries *vegan* and *labdsv*. We used groups suggested by the cluster models to label each sample point in the ordination plots.

Candidate environmental predictors included in the models were selected based on expected or well described, relationships with stream biota, although we also attempted to include a small number of environmental factors that were more indirect or perhaps exploratory. The significance of the environmental factors was tested in *vegan* via simulation. Environmental vectors are shown on ordination plots using a Bonferroni corrected alpha value (that varied based on the number of environmental variables included in each model).

2.4 Bioassessment: multimetric indices

Bioassessment is, generally speaking, the use of biologically based response measures to assess and monitor natural systems (Barbour et al. 2000). We use the approach to further meet objective four (determine the status for select sites in a suite of response measures) as a synthetic way to estimate stream status. We use a multimetric index (MMI; classically known as an index of biotic integrity or IBI) as our primary way of estimating ecological integrity. MMIs synthesize data from multiple levels of biological organization with the goal of deriving a single index that reflects the overall effects of disturbance on stream integrity.

2.4.1 Macroinvertebrate existing models

MMI models combine several submetrics that incorporate aspects of the autecology or how the macroinvertebrate community at a site is structured given the suite of stressors impacting it. Most metrics are based on the presence/absence or sometimes relative abundance of taxa in a sample weighted by autecological attributes (i.e., the tolerance of a taxon to a specific environmental condition, such as sediment or nutrient concentration). Metrics that describe characteristics of biota that change in predictable or interpretable ways with anthropogenic stress (water chemistry, habitat conditions, landscape composition, etc.) are ideal and selected for inclusion in the final model. MMI models are empirical in that they are built from and calibrated by streams that are known to be in reference or degraded condition. Jessup et al. (2006) developed the set of current Montana MMI metrics. These models discriminate well between reference and degraded sites, are ecologically meaningful (mechanisms of responses can be explained), and represent diverse types of information (multiple metric categories). The most appropriate Montana DEQ MMI for Glacier is the "Mountain" version of the MMI. This model includes seven component metrics (with the expected relationship with increasing disturbance inside parentheses): Ephemeroptera Taxa Richness (-), Plecoptera Taxa Richness (-), % EPT (Ephemeroptera (mayflies), Trichoptera (caddisflies), and Plecoptera (stoneflies)) (-), % Non-Insect (+), % Predator (-), Burrower Taxa Percent (+), and the Hilsenhoff Biotic Index (Nutrients) (+). We include component metrics of the MMI to aid in its interpretation.

A RIVPACS (River Invertebrate Prediction and Classification model) (Hawkins et al. 2000) is used to predict the expected (E) macroinvertebrate taxa at each SEI site that should occur given natural (i.e., reference) environmental characteristics. Specifically, these models describe how probabilities of capture of taxa vary across naturally occurring environmental gradients. Expected taxa are those specific taxa that should occur in a sample collected from a site with specific environmental features, assuming that site was in reference condition. By sampling the actual or observed (O) assemblage at the site, the simple ratio of O and E or a Bray-Curtis index comparing O and E estimates the taxonomic completeness of the assemblage. RIVPACS models are calibrated only with reference site data, and the accuracy and precision of RIVPACS assessments depend solely on how well models predict the taxa expected under reference conditions. Two Montana RIVPACS models currently exist (Jessup et al. 2006; Montana DEQ 2012b) – we include the 2005 model in this report as the 2011 model was deemed to not be well suited to Glacier. We include RIVPACS results based on a probability of capture greater than 0.5 (which reduces error introduced by rare taxa). Montana DEQ thresholds are for O:E and probability of capture > 0.5. We also include a Bray–Curtis measure of the distance between O and E for each sample. The Bray Curtis (BC) has some advantages over O:E. Montana DEQ recommends using both indices (Montana DEQ 2012b). In particular, the BC index facilitates determining if expected reference taxa are being replaced by more tolerant taxa (i.e., indicative of a non-reference state) – often O:E may just indicate an increase in taxa diversity. O:E is relatively insensitive to stress-induced shifts in taxonomic composition that have little net effect on the number of reference-site taxa (Hawkins et al. 2000; Davies and Jackson 2006). The BC index is most useful whenever a high (i.e., good) O:E score results from a sample collected from a known stressed stream.

2.4.2 Diatom existing models

Montana DEQ's current approach to bioassessment with diatoms uses pollutant-diagnosing biological metrics based on stressor-specific increaser diatom taxa, as described in

Teply (2010a, b). These tools are intended to assess specific impairment to aquatic life use support. "Increaser Taxa" were identified from a large sample of sites across the state with known impairments. Taxa that, as a group, exist in detectable amounts in streams with the Northern Rockies Ecoregion and demonstrate a meaningful, measurable, and significant response to sediment, nutrients, or metals were placed on cause-specific lists. Discriminant analysis was then used to evaluate the significance and reliability of candidate Increaser Taxa lists in predicting impaired and non-impaired streams using a validation dataset. A single threshold (criteria) set by Montana DEQ at a 50% probability for the percent relative abundance of increaser taxa that indicates likely impairment was generated by cause and stream type/ecoregion. However, the discriminant models can also be used to directly calculate the probability that a sample represents impaired conditions (for sediment and nutrients) for any percent relative abundance. We report the proportion of SEI samples with increaser taxa and the probabilities of impairment derived from the discriminant models.

2.4.3 Glacier specific multimetric model

We develop Glacier-specific models for macroinvertebrates and diatoms that respond to the suite of anthropogenic and natural stressors or drivers in Glacier. Schoolmaster, Grace, and Schweiger (2012), Schoolmaster, Grace, et al. (2012), and Schoolmaster et al. (2013) refine the theory behind MMIs and present the methods we use in detail. Overall, this modeling approach requires fewer assumptions and is more efficient with the given information than classic MMI methods (for example as used by Montana DEQ); thus, it represents an important advance for creating synthetic bioassessments of system response.

Despite the widespread use of MMIs, there is uncertainty about why this approach can be effective. We developed a quantitative theory that illustrates how the properties of candidate metrics relate to MMIs generated from those metrics. We used this theory to generate an optimal number of metrics to comprise an MMI, to deal with correlations among metrics and their impacts on the performance of an MMI index derived from those metrics, and to decide whether a metric will improve the performance of an index or not. In general, the criterion defining such conditions depends nonlinearly on the signal of the disturbance gradient, the noise (error) of the metric, and the correlation of the metric errors. We construct MMIs from a set of candidate metrics and a measure of human disturbance (HDI). The algorithm uses each metric to inform a candidate MMI, and then uses information-theoretic principles to select MMIs that capture the information in the multidimensional system response from among possible MMIs. Such an approach creates a purely empirical MMI or can, optionally, be influenced by expert opinion or biological theory through the use of a weighting vector to create value-weighted MMIs. When compared to other methods, our algorithmic approach results in MMIs that are more predictive and comprise fewer metrics. We also control for the potentially confounding influences of environmental covariates in the construction of SEI MMIs. Most common approaches to handling covariates are based on simple notions of statistical control, leaving the causal implications of covariates and their adjustment unstated. We use graphical models to examine some of the potential impacts of environmental covariates on the observed signals between human disturbance and potential response metrics. Environmental covariates can both obscure and exaggerate the effects of human disturbance on individual metrics, potentially having very misleading effects on identifying system responses. We use a "whole set" solution that models both environmental and human disturbance effects simultaneously. This whole-set modeling approach requires fewer assumptions and is more efficient with the given information than the more commonly applied reference-set approach; thus, it represents a major advance for identifying metrics of system response.

Key features of the approach include: 1) control of potentially confounding influences of environmental covariates using a strategy based on causal graphical models (key in wilderness parks like Glacier where stream condition can vary markedly along natural gradients), 2) use of the complete dataset to adjust for environmental gradients, simultaneously considering the effects of disturbance and environmental covariates on metrics in a single model, not a series of residualized adjustments as in other methods that require an a priori classification of sites into reference and non-reference, 3) a statistically optimal number of metrics are in a final MMI, 4) accounting for correlations among candidate component metrics and their impacts on the performance of the MMI, 5) incorporation of metrics in final MMI index only if they improve the performance of the model – this process depends nonlinearly on the signal of the disturbance gradient, the noise (error) of the metric, and the correlation of the metric errors, and 6) finally, use of an information-theoretic model selection approach to assemble and select the final MMI – this evaluates all possible combinations of component metrics and guarantees a statistically best model for any empirical dataset.

A summary of the steps used to create an MMI is given in

Figure D1 and is as follows:

1. Develop conceptual graphical model of the relationships amongst disturbance, metrics, and environmental covariates. These can be based on ecological knowledge and/or other models of patterns in the data.
2. Assemble disturbance indices (i.e., human disturbance index (HDI) or ungulate disturbance index (UDI)).
3. Assemble set of candidate bioassessment metrics.
4. Evaluate all possible bioassessment metrics for interpretability (expert opinion), completeness (remove any with missing and/or 0 values below a threshold of 25%), and multicollinearity (remove one from pairs with an r > 0.95, choosing those that are more interpretable).
5. Construct MMI:
   A. Reflect metrics that are positively correlated with disturbance to ensure each metric (and final MMI) is negatively correlated with disturbance.
   B. Adjust metrics for important covariates using an approach that uses all available data to model metrics as a function of known gradients and disturbance simultaneously.
   C. Scale metrics from 1 to 10 (Blocksom 2003).
   D. Select an initial metric (m1) to include in the MMI. This selection can be made arbitrarily since all metrics will eventually be used as an initial metric.
   E. Add m1 to each of the rest of the metrics, mj, site-by-site.
   F. For each mj, find which combination m1 + mj has the strongest negative correlation with disturbance. Select that one.
   G. Record the correlation (or other statistic) of the relationship between the assembled index with disturbance.
   H. Add the index to each of the remaining metrics mj , site-by-site.
   I. Find the combination of index + mj that has the strongest negative correlation with disturbance. Select this as an MMI based on AIC scores.
      i. Near equivalent (statistically the same) models are reported, such that final selection may also be based on the metrics included in each.
      ii. A model averaging approach is also used that creates an MMI as a matrix product of all equivalent MMIs and their AIC scores as weights. Component metrics within this model are the combined list from all near equivalent MMIs.

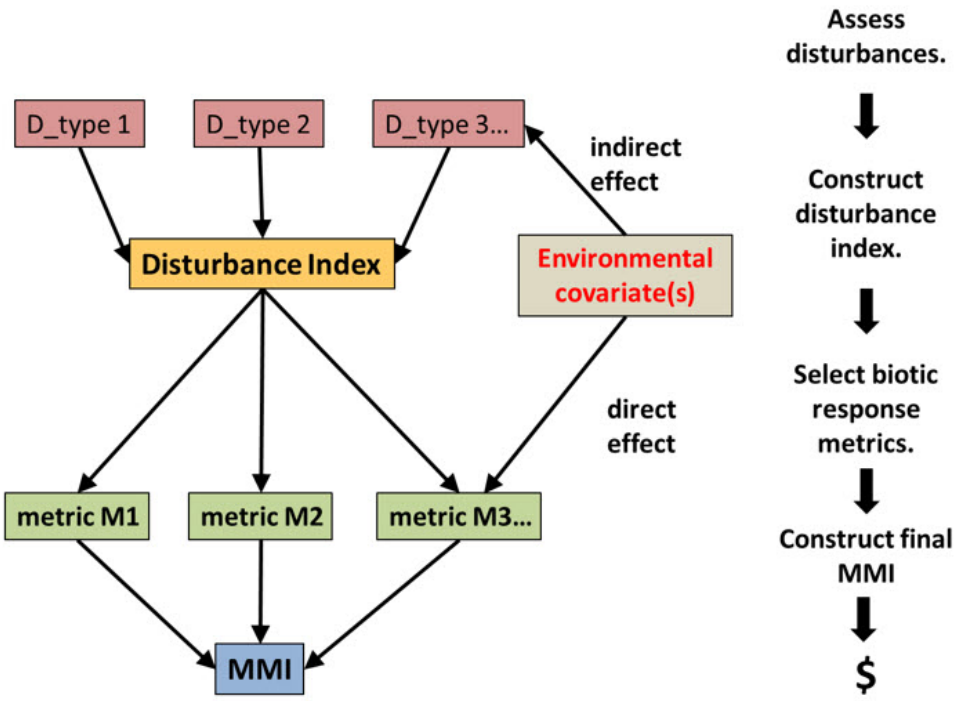


Figure D1. General flowchart for creating a multimetric index (MMI).

2.5 Physical habitat metrics

Kaufmann et al. (1999), and references within, define physical habitat as structural attributes of stream habitat that influence or provide sustenance to organisms within a stream. By definition this excludes water chemistry, such as water clarity, temperature, and light intensity. It does include biological aspects, such as riparian vegetation and large woody debris in and near the channel, because of their role in modifying habitat structure. Many aspects of stream habitat can be both a response to external disturbances and a measure of stress on the ecological condition of streams. However we generally treat physical habitat as a stressor on stream ecological condition. This is most obvious with our estimates of human disturbance, including the derived HDI summarized above, which are included as key aspects of stream habitat.

The large number of raw physical habitat measures collected during an SEI sample event are summarized over all subsamples in a site (see Figure 7 in the main narrative) into multiple metrics of physical habitat, as by design the SEI protocol uses the sample reach scale. Many physical habitat metrics are synthetic, integrating diverse facets over space and time (e.g., Kaufmann et al. 2008). Using guidance in Kaufmann et al. (1999), Stoddard et al. (2005), and USFWS (1998), we focus on 33 metrics in this report (selected from the many available) .These include summaries of areal cover estimates, more detailed and specific approaches for estimating woody debris, residual pool characteristics, sinuosity, and bed stability.

3 Population scale status: design based

For population scale status (objective two) we use design-based analysis. This is a less familiar approach than model-based analyses; however, it is a central component of any network protocol that includes a population scale perspective and survey designs such as stream monitoring at Glacier. Design-based analyses are well specified (Horvitz and Thompson 1952; Overton and Stehman 1996; Stevens 1997) and are the foundation of long-established analyses used in socioeconomics, politics, medicine and other fields. While beyond our scope here, in summary, design-based analyses use the inclusion probabilities (or sampling weights) from the design to extrapolate results or provide inference to unsampled elements of the target population. Results from design-based analyses apply (with the precision given in a confidence interval or standard error about an estimate) to all sampleable streams in Glacier in 2010. This is a fundamentally important aspect of SEI monitoring at Glacier.

Design-based inference uses a suite of algorithms detailed in Horvitz and Thompson (1952) and Diaz-Ramos et al. (1996) and implemented in the R library spsurvey (Kincaid and Olsen 2015). We report population means, 95% confidence intervals to the means, and standard errors (vs. a standard deviation, as our interest is in how we expect results to vary from a population mean). Confidence intervals and standard errors are based on estimates of variance that take advantage of the properties of a GRTS (Generalized Random-Tessellation Stratified) design. Known as a local neighborhood variance (Stevens and Olsen 2004), it provides estimates 20 to 60% smaller (i.e., more precise) than traditional survey-design variance estimators.

We report design-based results for most core SEI responses, including bioassessment metrics as introduced above, in tables and plots of the cumulative distribution of estimated values for a response (cumulative distribution functions or "CDF"s). CDFs include the 95% confidence intervals around the estimated probability. Where assessment points are known, CDFs facilitate interpretation by locating the proportion and/or real unit-based percentage of the response that is above or below the assessment point. We also include simple pie charts with CDFs for responses with assessment points, although these limit the inclusion of estimates of the variance around a value and should be used with caution.

Appendix E: Glacier National Park Ecoregional Reference Sites

For references in this appendix please see the literature cited section that follows the main narrative.

Much of the following text is borrowed from Suplee et al. (2005).

1 Overview

Glacier is embedded in the Northern Rockies and Canadian Rockies Ecoregions (see Figure 8). Monitoring sites on streams in these ecoregions that are expected to be in a reference state are identified by Montana DEQ and EPA. We use the designation from our partners for all ecoregion sites.

Given our large and representative sample of Glacier's streams in 2007–2009, we augment the population of ecoregional reference sites by applying the Montana DEQ methods to SEI sites. This increases the sample size and helps link assessment points and reference conditions to the population of reference streams in Glacier. We present a summary of the Montana DEQ methods here (they are very similar to those used by the EPA as they were developed in tandem and by staff in both agencies; T. Laidlaw, 2012, pers. comm.).

The Montana DEQ methods for selecting reference sites use a suite of variables that filter candidate sites based on their physiochemical and landscape context.

An evaluation process (Suplee et al. 2005) was developed and used to assess each candidate reference site in a consistent way. The process consisted of performing quantitative watershed and water-quality analyses for each site, as well as qualitative assessments of stream health and condition using a set of criteria and best professional judgment (BPJ). Each quantitative analysis or BPJ criterion evaluated some aspect of stream or watershed condition that could potentially impact water chemistry and aquatic life. Sixteen BPJ criteria, including bank erosion, sediment deposition, grazing impacts, cumulative impacts from multiple causes, site-specific data sufficiency, impacts from land use based on the proportion of agriculture, numeric water-quality standards exceedances for heavy metals, impacts from mines, road density, and timber-harvest intensity were used to create the final list of reference sites. The screens were constructed from the qualitative BPJ assessments and also from numeric values identified as impact thresholds in the quantitative analyses, and addressed factors operating at the watershed-scale, site-specific scale, and, in many cases, both. *To make the final list, a site had to pass each applicable screen. Sites that passed all applicable screens can be considered general-purpose reference sites, since they were found to be in an unimpacted condition for all categories.*

The Montana DEQ extends the concept by drafting definitions for two levels (tiers) that meet the state's naturally occurring or reference definition, but which more specifically describe the gradient of conditions that may be expected. This is conceptually similar to our definition of pristine reference and reference states. The definitions for each tier are as follows:

> Tier 1 — Natural Condition: The characteristics of a waterbody that is unaltered from its natural state, or there are no detectable human-caused changes in the completeness of the structure and function of the biotic community and the associated physical, chemical, and habitat conditions. All numeric water chemistry standards must be met and all beneficial uses must be fully supported unless impacts are clearly linked to a natural source. The natural condition is the highest attainable biological, chemical, physical, and riparian condition for waterbodies.
>
> Tier 2 — Minimally Impacted Condition: The characteristics of a waterbody in which the activities of man have made small changes that do not affect the completeness of the biotic community structure and function and the associated physical, chemical, and habitat conditions, and all numeric water chemistry standards are met and all beneficial uses are fully supported unless measured impacts are clearly linked to a natural source. Minimally impacted conditions can be used to describe attainable biological, chemical, physical, and riparian habitat conditions for waterbodies with similar watershed characteristics within similar geographic regions and represent the waterbody's best potential condition.

Waterbodies that meet the conditions described in either of the two definitions above may be used as reference sites, since both definitions fall under the broader definition of naturally occurring found in the assessment area.

An additional class, Tier 3, describes waterbodies that have a degree of impairment sufficient to generally warrant listing on the state's 303(d) list of impaired waterbodies:

> Tier 3 — Moderately Impaired Condition: The characteristics of a waterbody in which the activities of man

have made obvious changes to the completeness of the biotic community structure and function and the associated physical, chemical, and riparian habitat conditions, but the impacts have not caused a major displacement of sensitive taxa and acute numeric water chemistry standards are not exceeded.

2 Scoring Montana DEQ sites

For each candidate ecoregion site, each criterion was assigned a score of 1 (reference condition), 0 (stressed condition), or ND (insufficient data to assess) – see Table E1 for an example. For example, if examination of aerial photos showed few or no roads in the upstream watershed, that criterion would receive a 1. Reviewers also recorded notes as to why a criterion was given a particular score. Finally, based on the totality of information reviewed, an overall condition rating for the site was made by indicating if the stream site was tier 1 (natural condition), tier 2 (minimally impacted) or tier 3 (non-reference). A stream site could have been rated as tier 4 or 5; however, only sites of fairly high quality made it to the candidate list to begin with, and we did not identify any sites that rated 4 or 5. Reviewers had the discretion to decide which data were most important in determining a site's tier level. It was important that reviewers recorded their assessment notes with sufficient detail that a second reviewer could understand why a particular tier rating was made.

It should be noted that locating stream sites that rigidly fit the tier 1 definition that there be "no detectable human-caused changes in the completeness of the structure and function of the biotic community" may be very difficult to achieve, even in some wilderness areas, given the degree to which nonnative salmonids were actively stocked in the 19th and 20th century in mountainous areas of Montana and the West (Hanzel 1959; Brown 1971; Moyle et al. 1976; Liknes and Gould 1987). Streams that received a tier 1 rating by Montana DEQ should be viewed as having the absolute minimal human influences observable.

When applied to Glacier SEI sites (Table E2), 35 (out of 49) sites were classified as in reference condition (with a tier 1 designation), 10 were in a tier 2 condition, and 4 were in a non-reference state (tier 3).

Table E1. Example of Montana Department of Environmental Quality (DEQ) criteria used to evaluate reference and stressed conditions for cold water streams. In this example, the large number of zeros resulted in a tier 3 (non-reference) rating. ND = no data, 0 = not in reference condition, 1 = in reference condition.

Category	Indicator evaluated	Reference criteria (1)	Stressed criteria (0)	Reference condition score
Physical Habitat Category	Road densities (secondary data)	Minimal number of roads and roads are not close to streams.	>4 miles/ sq. mile	0
	New and old timber harvests (secondary data)	Minimal harvest activities, outside of the riparian areas; timber management activities attempt to mimic a natural fire regime.	Extensive harvesting within watershed (>25%); harvests occurring within riparian area.	0
	Percent surface fines	Low fines, representative of the geologic conditions.	>30% fines less than 2 mm.	ND
	Sediment deposition	Between 0–25% of the substrate surrounded by fine sediment.	Greater than 75% of the substrate surrounded by fine sediment.	0
	Bank erosion	No erosion or limited to "natural" occurrences. Stable banks.	Extensive bank erosion caused by anthropogenic activities.	0
	Bank vegetation	Over 90% of the streambank covered by stabilizing vegetation; vegetated zone width >100 feet.	Less than 50% of the streambank covered by stabilizing vegetation; vegetated zone width <10 feet.	0
	Permitted point sources	Few to no point source discharges in the watershed. Site located greater than 5 miles downstream or above the permitted discharge.	Many point source discharges present. Site located less than 2 miles downstream of a point source discharge.	1
	Land under agricultural use	Minimal to no agricultural use occurring.	Extensive agricultural activities present and may occur within the riparian area.	1
	Grazing use	Light grazing occurs; impacts are minimal.	Heavy grazing causing moderate impacts.	ND
	Mining sites	Site not located in DEQ priority abandoned hardrock mining subbasin; or, basin mine density low.	Site located in DEQ priority abandoned hardrock mining subbasin; or, basin mine density high.	1
Professional Judgment Category	Anecdotal evidence from non-standard sources	No anecdotal evidence of significant disturbance encountered.	Evidence of significant recent or persistent physical or chemical disturbance is credible and verifiable.	ND
	Field observations not listed as criteria	No source of stress or evidence of existing stress exists.	A source of stress or evidence of existing stress exists and is not considered in other criteria.	0
	Aesthetics	Site has exceptional aesthetic quality without apparent disturbances in watershed, riparian areas, or channel.	Aesthetically unappealing due to elements that probably affect water resource quality (must be described).	0
	Other determinations	Other agency/entity has determined that the site is of reference quality using acceptable documented procedures or non-biological criteria.	Other agency/entity has determined that the site is stressed using documented procedures or non-biological criteria	ND
On 2004 303(d) list (or re-assessment list)?				NO
Probable tier level (1, 2, 3, 4, 5)				**3**

Table E2. Final classifications of Glacier National Park Stream Ecological Integrity sites based on the Montana Department of Environmental Quality reference site protocol (by which the table is sorted), the Stream Ecological Integrity Human Disturbance Index (HDI), the Glacier Macroinvertebrate MMI (MMI_{Gm}), and the Glacier Diatom MMI (MMI_{Gd}). Tier 3 = non-reference condition, Tier 2 = intermediate condition, Tier 1 = pristine reference condition.

Site ID	Site name	Montana DEQ expected reference class	HDI	HDI ecoregional assessment point reference classes	MMI_{Gm}	Macroinvertebrate reference class	$MMI1_{Gd}$	Diatom reference class
G01	Divide Creek	Tier 3	0.60	Moderate	3.78	NonReference	3.91	Intermediate
G03	Canyon Creek	Tier 3	0.94	Major	3.80	NonReference	3.40	NonReference
G04	Big Creek	Tier 3	0.97	Major	3.13	NonReference	3.67	Intermediate
G02	Coal Creek	Tier 3	1.00	Major	3.68	NonReference	2.17	NonReference
091	South Fork Cut Bank Creek	Tier 2	0.00	Negligible	6.78	PristineReference	7.05	PristineReference
095	Saint Mary River	Tier 2	0.00	Negligible	5.76	PristineReference	6.37	PristineReference
G07	Kennedy Creek	Tier 2	0.00	Negligible	5.69	Reference	5.09	Reference
041	Camas Creek	Tier 2	0.10	Minor	5.01	Intermediate	4.38	Intermediate
009	North Fork Flathead River	Tier 2	0.37	Moderate	4.09	Intermediate	4.44	Intermediate
002	N. Fork Flathead River	Tier 2	0.39	Moderate	5.11	Intermediate	3.94	Intermediate
013	N. Fork Flathead River	Tier 2	0.51	Moderate	4.05	Intermediate	4.20	Intermediate
G06	Fish Creek	Tier 2	0.76	Moderate	4.25	Intermediate	3.09	NonReference
032	Railroad Creek Trib	Tier 2	0.88	Moderate	3.98	Intermediate	2.33	NonReference
093	Rubideau Creek Trib	Tier 2	0.89	Moderate	3.49	NonReference	3.17	NonReference
003	Belly River	Tier 1	0.00	Negligible	6.43	PristineReference	6.60	PristineReference
004	Nyack Creek	Tier 1	0.00	Negligible	5.39	Reference	5.53	Reference
006	Starvation Creek	Tier 1	0.00	Negligible	5.93	PristineReference	4.87	Reference
007	Mineral Creek	Tier 1	0.00	Negligible	5.33	Reference	5.21	Reference
008	Lincoln Creek Trib	Tier 1	0.00	Negligible	5.18	Reference	4.76	Intermediate
010	Boundary Creek	Tier 1	0.00	Negligible	6.58	PristineReference	4.68	Intermediate
011	Hudson Bay Creek	Tier 1	0.00	Negligible	5.34	Reference	5.40	Reference
014	Belly River	Tier 1	0.00	Negligible	5.90	PristineReference	5.80	PristineReference
016	Ole Creek	Tier 1	0.00	Negligible	5.77	PristineReference	5.43	Reference
017	Bowman Lake Trib	Tier 1	0.00	Negligible	6.40	PristineReference	5.45	Reference
020	Thompson Creek Trib	Tier 1	0.00	Negligible	5.91	PristineReference	5.33	Reference
025	Howe Creek	Tier 1	0.00	Negligible	5.22	Reference	4.74	Intermediate
033	Waterton River	Tier 1	0.00	Negligible	5.84	PristineReference	6.34	PristineReference
034	Akokala Creek	Tier 1	0.00	Negligible	5.76	PristineReference	5.43	Reference

Table E2 (continued). Final classifications of Glacier National Park Stream Ecological Integrity sites based on the Montana Department of Environmental Quality reference site protocol (by which the table is sorted), the Stream Ecological Integrity Human Disturbance Index (HDI), the Glacier Macroinvertebrate MMI (MMI_{Gm}), and the Glacier Diatom MMI (MMI_{Gd}). Tier 3 = non-reference condition, Tier 2 = intermediate condition, Tier 1 = pristine reference condition.

Site ID	Site name	Montana DEQ expected reference class	HDI	HDI ecoregional assessment point reference classes	MMI_{Gm}	Macroinvertebrate reference class	$MMI1_{Gd}$	Diatom reference class
049	Dutch Creek	Tier 1	0.00	Negligible	5.82	PristineReference	4.57	Intermediate
097	Waterton River	Tier 1	0.00	Negligible	5.73	Reference	4.44	Intermediate
098	Parke Creek	Tier 1	0.00	Negligible	5.35	Reference	4.50	Intermediate
129	Quartz Creek	Tier 1	0.00	Negligible	6.11	PristineReference	5.74	PristineReference
S05	Ole Creek	Tier 1	0.00	Negligible	6.45	PristineReference	5.91	PristineReference
005	Quartz Creek	Tier 1	0.01	Minor	6.25	PristineReference	5.52	Reference
027	Red Eagle Creek	Tier 1	0.01	Minor	5.45	Reference	5.41	Reference
S04	Reynolds Creek	Tier 1	0.02	Minor	6.49	PristineReference	4.80	Intermediate
015	Appistoki Creek	Tier 1	0.06	Minor	6.14	PristineReference	5.97	PristineReference
109	Apgar creek	Tier 1	0.07	Minor	5.44	Reference	5.97	PristineReference
S01	Swiftcurrent Creek	Tier 1	0.08	Minor	5.43	Reference	6.42	PristineReference
108	Nyack Creek	Tier 1	0.08	Minor	5.52	Reference	5.71	PristineReference
018	Bowman Creek	Tier 1	0.11	Minor	5.27	Reference	5.28	Reference
105	Camas Creek	Tier 1	0.14	Minor	4.86	Intermediate	5.55	PristineReference
104	M. Fork Flathead River	Tier 1	0.15	Minor	4.80	Intermediate	4.78	Intermediate
012	M. Fork Flathead River	Tier 1	0.23	Minor	4.10	Intermediate	5.26	Reference
101	Camas Creek	Tier 1	0.24	Minor	4.80	Intermediate	3.80	Intermediate
037	McGee Creek	Tier 1	0.35	Minor	5.02	Intermediate	4.95	Reference
022	N. Fork Flathead River Border	Tier 1	0.35	Moderate	4.49	Intermediate	5.14	Reference
100	McDonald Creek	Tier 1	0.44	Moderate	4.72	Intermediate	4.65	Intermediate
023	McDonald Creek	Tier 1	0.52	Moderate	4.53	Intermediate	4.03	Intermediate

Appendix F: Exploratory Model Details

The following presents select details for exploratory model results. For additional output and clarification, contact the network.

For references in this appendix please see the literature cited section that follows the main narrative.

1 Exploratory model of human disturbance

Model of Glacier National Park Human Disturbance Index (HDI) in 2007–2009. Final model selected using Akaike Information Criterion (AIC) and expert opinion from 18 candidate variables. Relative importance is the total amount of explained variance for each variable expressed as a percentage. Watershed is treated as a factor and all estimates are relative to the Hudson Bay drainage. The relative importance value for watershed is for all groups combined.

```
Call:
lm(formula = HDI ~ factor(Watershed) + RipBuffDist + DistRoad +
    Elev + Burn + MinCatchTemp + Buildings, data = env)

Residuals:
     Min       1Q   Median       3Q      Max
-0.32449 -0.07579 -0.00114  0.08750  0.49376

Coefficients:
                                      Estimate Std. Error t value Pr(>|t|)
(Intercept)                          1.5834829  0.3667754   4.317 0.000105 ***
factor(Watershed)Middle Fork Flathead -0.0530675  0.1217567  -0.436 0.665349
factor(Watershed)Missouri             0.0941619  0.1485322   0.634 0.529815
factor(Watershed)North Fork Flathead  0.1680454  0.1421693   1.182 0.244359
RipBuffDist                          -1.4079470  0.9725979  -1.448 0.155716
DistRoad                             -0.0815365  0.0224546  -3.631 0.000810 ***
Elev                                 -0.0006145  0.0002336  -2.631 0.012140 *
Burn                                 -0.0490106  0.0306927  -1.597 0.118379
MinCatchTemp                          0.0183638  0.0133515   1.375 0.176854
Buildings                             0.2321365  0.2422575   0.958 0.343854
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.1883 on 39 degrees of freedom
Multiple R-squared:  0.7013,    Adjusted R-squared:  0.6324
F-statistic: 10.17 on 9 and 39 DF,  p-value: 7.472e-08
```

```
9 Regressors:
Some regressors combined in groups:
        Group  factor(glac_drain5) : `factor(glac_drain5)`Middle Fork Flathead `factor(glac_drain5)`Missouri
`factor(glac_drain5)`North Fork Flathead

 Relative importance of 7 (groups of) regressors assessed:
 factor(glac_drain5) log(qr1 + 1) log(disttoroad) elev_site_m log(burn_1984tocurrent + 1) min_catch_streamtemp
log(buildadmincnt_km2 + 1)

Proportion of variance explained by model: 70.13%
Metrics are normalized to sum to 100% (rela=TRUE).

Relative importance metrics:

                                  lmg
factor(glac_drain5)         0.12561232
log(qr1 + 1)                0.08081414
log(disttoroad)             0.42387270
elev_site_m                 0.16834153
log(burn_1984tocurrent + 1) 0.07229215
min_catch_streamtemp        0.02163756
log(buildadmincnt_km2 + 1)  0.10742961
```

2 Exploratory models of water chemistry

2.1 Stream water temperature

Model of base flow late summer midday instantaneous stream water temperature in 2007–2009 in Glacier National Park. Final model selected using Akaike Information Criterion (AIC) and expert opinion from 24 candidate variables. Relative importance is the total amount of explained variance for each variable expressed as a percentage.

```
  Call:

  lm(formula = temp_c.1 ~ julianday + elev_site_m + log(glacierper +

      1) + max_air_temp_30yr + log(q_cms + 1) + xembed + xcdenbk +

      xdepth + lrbs_bw5, data = env)
```

Residuals:

```
    Min      1Q  Median      3Q     Max
-2.4866 -1.0385 -0.1873  1.0400  3.6843
```

Coefficients:

	Estimate	**SE**	**t**	**p**
(Intercept)	-39.90	14.95	-2.67	0.01
julianday	-0.07	0.01	-5.39	0.00
elev_site_m	0.02	0.01	4.55	0.00
log(glacierper	3.15	0.72	4.36	0.00
max_air_temp_30yr	3.57	0.80	4.46	0.00
log(q_cms	4.35	1.13	3.84	0.00
xembed	0.09	0.02	3.93	0.00
xcdenbk	0.04	0.02	2.24	0.03
xdepth	-0.15	0.03	-6.16	0.00
lrbs_bw5	2.66	0.67	3.99	0.00

```
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Residual standard error: 1.592 on 30 degrees of freedom
  (9 observations deleted due to missingness)
Multiple R-squared:  0.7683,    Adjusted R-squared:  0.6988
F-statistic: 11.05 on 9 and 30 DF,  p-value: 2.307e-07

> m3_importance
Response variable: temp_c.1
Total response variance: 8.411554
Analysis based on 40 observations

9 Regressors:
Proportion of variance explained by model: 76.83%
Metrics are normalized to sum to 100% (rela=TRUE).
```

```
  Relative importance metrics:
                                lmg
  julianday                 0.21032825
  elev_site_m               0.11465207
  log(glacierper            0.07825009
  max_air_temp_30yr         0.11515521
  log(q_cms                 0.08142307
  xembed                    0.11089043
  xcdenbk                   0.02701393
  xdepth                    0.20893914
  lrbs_bw5                  0.0533478
```

2.2 Total phosphorous

Model of total phosphorous (mg/l) in 2007–2009 in Glacier National Park. Final model selected using Akaike Information Criterion (AIC) and expert opinion from 31 candidate variables. Relative importance (Rel. Imp %) is the total amount of explained variance for each variable expressed as a percentage. Stream order is treated as a factor and all estimates are relative to stream order three (the most common type). Its relative importance value is for all groups combined.

```
Call:
lm(formula = TotP ~ factor(StrmOrdr) + TSS + TotN + Prcp30 +
    Q + RipCvr + Wood + SubDia, data = env)

Residuals:
       Min         1Q     Median         3Q        Max
-0.0115920 -0.0021238 -0.0000107  0.0015273  0.0164574

Coefficients:
                      Estimate Std. Error t value Pr(>|t|)
(Intercept)          -4.950e-03  6.467e-03  -0.765  0.44927
factor(StrmOrdr)One   5.361e-03  3.781e-03   1.418  0.16539
factor(StrmOrdr)Two   4.334e-03  3.380e-03   1.282  0.20850
factor(StrmOrdr)Four -2.810e-03  2.427e-03  -1.158  0.25505
factor(StrmOrdr)Five -1.450e-03  3.671e-03  -0.395  0.69527
factor(StrmOrdr)Six   3.807e-03  8.171e-03   0.466  0.64424
TSS                   1.152e-03  2.390e-04   4.819 2.95e-05 ***
TotN                  3.609e-02  1.041e-02   3.466  0.00145 **
Prcp30               -7.888e-06  3.693e-06  -2.136  0.03997 *
Q                    -3.967e-03  1.901e-03  -2.087  0.04443 *
RipCvr                6.305e-03  2.670e-03   2.361  0.02409 *
Wood                 -2.158e-03  1.296e-03  -1.665  0.10504
SubDia                5.699e-03  2.775e-03   2.054  0.04777 *
```

```
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.005737 on 34 degrees of freedom
  (2 observations deleted due to missingness)
Multiple R-squared:  0.8311,    Adjusted R-squared:  0.7715
F-statistic: 13.94 on 12 and 34 DF,  p-value: 8.204e-10


  Relative importance metrics:

                                                 lmg       last        first
  factor(strahler)                          0.17558445 0.12904412 1.970373e-01
  solids.total.suspended.tss.suspended_nd 0.34441567 0.35656155 3.417464e-01
  nitrogen.total_nd                         0.34040168 0.18446145 3.886676e-01
  ppt_10mm_c_predicted                      0.03340828 0.07005877 2.959192e-03
  log(q_cms + 1)                            0.04868432 0.06690854 4.737271e-02
  xcmgw                                     0.03194350 0.08561247 2.196749e-02
  lv1w_msq                                  0.01105262 0.04258867 8.477284e-05
  plsub_dmm                                 0.01450948 0.06476444 1.645227e-04
```

3 Exploratory models of physical habitat

3.1 Observed : expected pool depth (habitat volume)

Model of ratio of observed to expected pool depths in 2007–2009 in Glacier National Park. Final model selected using Akaike Information Criterion (AIC) and expert opinion from 16 candidate variables. Relative importance is the total amount of explained variance for each variable expressed as a percentage.

```
Call:
lm(formula = OEpool ~ factor(eastwest) + hdi + elev_site_m +
    log(glacierper + 1) + log(xdepth + 1) + cvdpth + log(flow_cfs +
    1), data = env)

Residuals:
     Min       1Q   Median       3Q      Max
-0.55236 -0.14424  0.00068  0.14436  0.43760
```

```
Coefficients:
                     Estimate Std. Error t value Pr(>|t|)
(Intercept)           1.0292571  0.7402027   1.391  0.17291
factor(eastwest)West -0.3465747  0.1589216  -2.181  0.03581 *
hdi                  -0.5064297  0.1659770  -3.051  0.00426 **
elev_site_m          -0.0008239  0.0003707  -2.223  0.03261 *
log(glacierper + 1)  -0.1242619  0.0734450  -1.692  0.09930 .
log(xdepth + 1)       0.2602819  0.0554139   4.697 3.78e-05 ***
cvdpth                0.4457918  0.2773669   1.607  0.11674
log(flow_cfs + 1)     0.0643601  0.0318004   2.024  0.05045 .
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.2559 on 36 degrees of freedom
  (5 observations deleted due to missingness)
Multiple R-squared:  0.5988,    Adjusted R-squared:  0.5208
F-statistic: 7.676 on 7 and 36 DF,  p-value: 1.145e-05

> m2_importance
Response variable: OEpool
Total response variance: 0.1366845
Analysis based on 44 observations

7 Regressors:
factor(eastwest) hdi elev_site_m log(glacierper + 1) log(xdepth + 1) cvdpth log(flow_cfs + 1)
Proportion of variance explained by model: 59.88%
Metrics are normalized to sum to 100% (rela=TRUE).

Relative importance metrics:

                           lmg       last       first
factor(eastwest)    0.08909718 0.09397123 0.094268896
hdi                 0.18491939 0.18395406 0.187380221
elev_site_m         0.05460014 0.09760777 0.025060044
log(glacierper + 1) 0.05761717 0.05656117 0.121159754
log(xdepth + 1)     0.50774755 0.43592994 0.496470145
cvdpth              0.03395736 0.05104129 0.009444064
log(flow_cfs + 1)   0.07206121 0.08093454 0.066216874
```

3.2 Relative bed stability

Model of relative bed stability in 2007–2009 in Glacier National Park. Final model selected using Akaike Information Criterion (AIC) and expert opinion from 22 candidate variables. Relative importance is the total amount of explained variance for each variable expressed as a percentage.

```
Call:
lm(formula = lrbs_bw5 ~ factor(eastwest) + hdi + elev_site_m +
    log(glacierper + 1) + log(sub_dmm_nor + 1) + log(xdepth +
    1) + log(xbkf_h + 1), data = env)

Residuals:
     Min       1Q   Median       3Q      Max
-0.54651 -0.18420  0.02247  0.20390  0.49311

Coefficients:
                     Estimate Std. Error t value Pr(>|t|)
(Intercept)          -1.877536   0.816764  -2.299 0.027792 *
factor(eastwest)West -0.879355   0.212569  -4.137 0.000218 ***
hdi                  -0.707642   0.209137  -3.384 0.001816 **
elev_site_m          -0.002015   0.000515  -3.914 0.000415 ***
log(glacierper + 1)  -0.333207   0.089450  -3.725 0.000707 ***
log(sub_dmm_nor + 1)  0.643831   0.065884   9.772 2.10e-11 ***
log(xdepth + 1)       0.467475   0.088031   5.310 6.79e-06 ***
log(xbkf_h + 1)      -0.497196   0.204972  -2.426 0.020738 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.3083 on 34 degrees of freedom
  (7 observations deleted due to missingness)
Multiple R-squared:  0.8114,    Adjusted R-squared:  0.7726
F-statistic:  20.9 on 7 and 34 DF,  p-value: 1.354e-10

> m2_importance
Response variable: lrbs_bw5
Total response variance: 0.4178815
Analysis based on 42 observations

7 Regressors:
factor(eastwest) hdi elev_site_m log(glacierper + 1) log(sub_dmm_nor + 1) log(xdepth + 1) log(xbkf_h + 1)
Proportion of variance explained by model: 81.14%
Metrics are normalized to sum to 100% (rela=TRUE).
```

```
Relative importance metrics:

                            lmg       last        first
factor(eastwest)      0.04325251 0.09135087 1.615431e-02
hdi                   0.02615167 0.06111527 7.555782e-05
elev_site_m           0.03581920 0.08176013 1.299800e-03
log(glacierper + 1)   0.13707738 0.07407207 2.065875e-01
log(sub_dmm_nor + 1) 0.60364388 0.50975886 7.520368e-01
log(xdepth + 1)       0.13162481 0.15053390 2.384219e-02
log(xbkf_h + 1)       0.02243053 0.03140890 3.865858e-06
```

4 Exploratory models of biological responses

4.1 Exploratory models of RIVPACS metrics

Model of Montana DEQ 2005 RIVPACS O:E, all taxa (p > 0) (p = probability of capture) in 2007–2009 in Glacier National Park. Final model selected using Akaike Information Criterion (AIC) and expert opinion from 22 candidate variables. Relative importance is the total amount of explained variance for each variable expressed as a percentage. Stream order is treated as a factor and all estimates are relative to stream order three (the most common type). Its relative importance value is for all groups combined. East vs. West is treated as a factor and all estimates are relative to sites on the east side of the park.

```
Call:
lm(formula = oe_p_0 ~ factor(strahler) + factor(eastwest) + log(catch_area_m2) +
    hdi + log(distlake_closest) + log(tss + 1) + log(xwidth +
    1), data = env)

Residuals:
      Min        1Q    Median        3Q       Max
-0.245907 -0.070881 -0.000044  0.070645  0.307168

Coefficients:
                     Estimate Std. Error t value Pr(>|t|)
(Intercept)           -0.41063    0.70965  -0.579   0.5663
factor(strahler)Four  -0.17343    0.08695  -1.994   0.0535 .
factor(strahler)One   -0.24149    0.17647  -1.368   0.1794
factor(strahler)Six   -0.17719    0.10239  -1.730   0.0919 .
factor(strahler)Three -0.13465    0.10274  -1.311   0.1981
factor(strahler)Two   -0.38719    0.14515  -2.668   0.0113 *
factor(eastwest)West  -0.09362    0.05207  -1.798   0.0804 .
log(catch_area_m2)     0.09878    0.03997   2.471   0.0182 *
hdi                   -0.20104    0.07788  -2.581   0.0139 *
log(distlake_closest)  0.04171    0.01675   2.490   0.0174 *
log(tss + 1)          -0.07105    0.02983  -2.382   0.0225 *
```

```
log(xwidth + 1)       -0.14328    0.05735  -2.499   0.0170 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.1275 on 37 degrees of freedom
Multiple R-squared:  0.6554,    Adjusted R-squared:  0.553
F-statistic: 6.398 on 11 and 37 DF,  p-value: 8.294e-06

Relative importance metrics:

                            lmg      last      first
factor(strahler)      0.40440839 0.3556870 0.40099615
factor(eastwest)      0.02447393 0.0610401 0.02848889
log(catch_area_m2)    0.15859618 0.1153454 0.21718476
hdi                   0.07360442 0.1258371 0.01412085
log(distlake_closest) 0.07468015 0.1170811 0.03217923
log(tss + 1)          0.15296395 0.1071113 0.15223851
log(xwidth + 1)       0.11127299 0.1178980 0.15479161
```

4.2 Exploratory model of sediment increaser metric

Model of sediment increasers in the streams of Glacier National Park, 2007–2009. Final model selected using Akaike Information Criterion (AIC) and expert opinion from 26 candidate variables. Relative importance (Rel. Imp %) is the total amount of explained variance for each variable expressed as a percentage.

```
lm(formula = sed_inc ~ log(Burn + 1) + Lat + log(Lake) + OrthoP +
    FnGrvl + Pool, data = env)

Residuals:
      Min        1Q    Median        3Q       Max
-0.089323 -0.025845 -0.003602  0.024103  0.085736

Coefficients:
               Estimate Std. Error t value Pr(>|t|)
(Intercept)    2.501e-01  1.077e-01   2.321   0.0252 *
log(Burn + 1) -1.033e-02  4.601e-03  -2.245   0.0301 *
Lat           -9.379e-07  3.391e-07  -2.766   0.0084 **
log(Lake)      9.945e-03  4.819e-03   2.064   0.0453 *
OrthoP         1.076e+01  1.754e+00   6.137 2.52e-07 ***
FnGrvl         2.852e-03  9.936e-04   2.870   0.0064 **
Pool          -4.476e-01  2.120e-01  -2.111   0.0407 *
---
```

```
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.0407 on 42 degrees of freedom
Multiple R-squared:  0.5992,    Adjusted R-squared:  0.5419
F-statistic: 10.46 on 6 and 42 DF,  p-value: 4.434e-07

Relative importance metrics:

                     lmg       last        first
log(Burn + 1) 0.04137017 0.07487412 7.629409e-05
Lat           0.11758449 0.11364999 1.286573e-01
log(Lake)     0.05028740 0.06327012 4.559467e-02
OrthoP        0.57801830 0.55957359 6.150082e-01
FnGrvl        0.13378313 0.12240525 1.178168e-01
Pool          0.07895650 0.06622692 9.284674e-02
```

Appendix G: Taxa Lists

The following tables list taxa collected from 2007 to 2009 at all stream monitoring sample events in Glacier National Park.Table G1 lists macroinvertebrates. Table G2 lists diatoms. Table G3 lists soft bodied algae.

Table G1. Macroinvertebrate taxa list and relative abundances from Stream Ecological Integrity monitoring at Glacier National Park, 2007–2009. Total counts are followed by mean relative abundances. Macroinvertebrate taxa were identified by multiple taxonomists, so we use Operational Taxonomic Units (OTUs) to collapse identifications to comparable values. If taxa were identified at a level above family, we include this in the Family column.

Family (or higher)	Taxa (Rocky Mountain Network OTU)	Taxonomic Serial Number	Level of identification	Total count (2007–2009)	Mean relative abundance
Acari	*Acari*	733321	Subclass	976	1.77
Atractides	*Dixa*	125810	Genus	4	0.69
	Atractides	733321	Subclass	18	0.35
	Acentrella	100801	Genus	397	2.61
Aturus	*Acerpenna pygmaea*	206620	Species	5	0.84
	Dolichopodidae	136824	Family	5	0.15
	Aturus	733321	Subclass	1	0.15
Baetidae	*Centroptilum*	100873	Genus	7	0.32
	Plauditus	568553	Genus	19	1.10
	Diphetor hageni	568598	Species	236	1.27
	Baetis bicaudatus	100823	Species	219	1.86
	Baetis tricaudatus	100817	Species	1424	4.27
	Baetis flavistriga	100835	Species	678	5.18
	Callibaetis	100903	Genus	2	0.16
	Fallceon	568551	Genus	90	16.98
Baetiscidae	*Baetisca*	101494	Genus	3	0.23
Belostomatidae	*Belostoma*	103684	Genus	2	0.17
Blephariceridae	*Blephariceridae*	121227	Family	1	0.17
Brachycentridae	*Micrasema*	116958	Genus	67	0.44
	Brachycentrus	116906	Genus	107	0.53
	Brachycentridae	116905	Family	1	0.19
	Brachycentrus americanus	116912	Species	35	0.37
Caenidae	*Caenis*	101478	Genus	1	0.16
Calopterygidae	*Calopterygidae*	102043	Family	3	0.57
Capniidae	*Capniidae*	102643	Family	252	0.94
Ceratopogonidae	*Mallochohelea*	127338	Family	71	0.68
	Ceratopogoninae	127338	Family	287	1.47
	Forcipomyia	127152	Genus	2	0.19
	Ceratopogonidae	127076	Family	100	0.56
	Stilobezzia	127338	Family	1	0.15
Chironomidae	*Cryptochironomus*	129368	Genus	5	0.27
	Diamesa	128355	Genus	900	2.15
	Dicrotendipes	129428	Genus	3	0.25
	Cricotopus/Orthocladius	128457	Subfamily	44	4.08
	Cricotopus	128575	Genus	456	1.45
	Polypedilum	129657	Genus	680	1.84
	Potthastia	128408	Genus	144	0.85
	Procladius	128277	Genus	7	0.21

Table G1 (continued). Macroinvertebrate taxa list and relative abundances from Stream Ecological Integrity monitoring at Glacier National Park, 2007–2009. Total counts are followed by mean relative abundances. Macroinvertebrate taxa were identified by multiple taxonomists, so we use Operational Taxonomic Units (OTUs) to collapse identifications to comparable values. If taxa were identified at a level above family, we include this in the Family column.

Family (or higher)	Taxa (Rocky Mountain Network OTU)	Taxonomic Serial Number	Level of identification	Total count (2007–2009)	Mean relative abundance
Chironomidae (cont'd)	*Prodiamesa*	128452	Genus	1	0.17
	Constempellina	129884	Genus	277	3.34
	Conchapelopia	128236	Group	3	0.60
	Psectrocladius	129018	Genus	1	0.11
	Pseudochironomus	129851	Genus	12	0.92
	Pseudodiamesa	128416	Genus	19	0.29
	Pseudorthocladius	129052	Genus	8	0.36
	Cladotanytarsus	129873	Genus	193	2.17
	Corynoneura	128563	Genus	72	0.36
	Epoicocladius	128682	Genus	3	0.50
	Monodiamesa	128440	Genus	17	0.47
	Microtendipes	129535	Genus	503	2.97
	Micropsectra	129890	Genus	2491	3.06
	Ablabesmyia	128079	Genus	1	0.16
	Lopescladius	128811	Genus	23	0.55
	Parametriocnemus	128978	Genus	338	1.04
	Krenosmittia	128771	Genus	36	0.25
	Odontomesa	128446	Genus	8	0.28
	Hydrobaenus	128750	Genus	266	1.22
	Eukiefferiella	128689	Genus	1262	2.10
	Heterotrissocladius	128737	Genus	128	1.30
	Euryhapsis	128707	Genus	7	1.16
	Helopelopia	128131	Genus	9	0.75
	Heleniella	128730	Genus	12	0.49
	Limnophyes	128776	Genus	4	0.16
	Paracladopelma	129597	Genus	17	0.53
	Diplocladius	128670	Genus	3	0.29
	Parorthocladius	129011	Genus	22	0.31
	Paratendipes	129623	Genus	19	0.85
	Paratanytarsus	129935	Genus	10	0.28
	Paraphaenocladius	128989	Genus	3	0.28
	Rheocricotopus	129086	Genus	137	0.58
	Natarsia	128070	Genus	44	18.26
	Pentaneura	128215	Genus	12	0.26
	Nilotanypus	128202	Genus	9	0.25
	Pagastia	128401	Genus	548	1.43
	Orthocladius	128874	Genus	1795	2.98
	Orthocladiinae sp. (RAI Taxon # 0004)	128457	Subfamily	1	0.16
	Orthocladiinae sp. (RAI Taxon # 0001)	128457	Subfamily	2	0.29
	Orthocladiinae	128457	Subfamily	1357	3.73
	Phaenopsectra	129637	Genus	89	1.27
	Parakiefferiella	128968	Genus	68	0.63
	Synorthocladius	129161	Genus	6	0.24

Table G1 (continued). Macroinvertebrate taxa list and relative abundances from Stream Ecological Integrity monitoring at Glacier National Park, 2007–2009. Total counts are followed by mean relative abundances. Macroinvertebrate taxa were identified by multiple taxonomists, so we use Operational Taxonomic Units (OTUs) to collapse identifications to comparable values. If taxa were identified at a level above family, we include this in the Family column.

Family (or higher)	Taxa (Rocky Mountain Network OTU)	Taxonomic Serial Number	Level of identification	Total count (2007–2009)	Mean relative abundance
Chironomidae (cont'd)	*Brillia*	128477	Genus	90	0.46
	Boreoheptagyia	128343	Genus	6	0.17
	Boreochlus	127954	Genus	4	0.32
	Chironomini	129229	Tribe	36	1.22
	Stempellina	129962	Genus	34	0.47
	Stempellinella	129969	Genus	1129	2.50
	Stictochironomus	129785	Genus	117	1.99
	Sublettea	129975	Genus	43	0.68
	Robackia	129730	Genus	4	0.51
	Symposiocladius	128877	Genus	1	0.11
	Tanytarsini	129872	Tribe	313	2.27
	Tanypodinae	127994	Subfamily	176	1.34
	Tanytarsus	129978	Genus	632	1.39
	Thienemanniella	129182	Genus	86	0.44
	Thienemannimyia	128236	Group	9	0.84
	Thienemannimyia Gr.	128236	Group	542	1.51
	Rheotanytarsus	129952	Genus	149	0.95
	Xenochironomus xenolabis	129838	Species	2	0.16
	Trissopelopia	128251	Genus	1	0.16
	Tvetenia	129197	Genus	594	1.12
	Zavrelimyia	128259	Genus	11	0.62
	Chaetocladius	128520	Genus	17	0.48
	Chironomini	129229	Tribe	7	0.19
	Cardiocladius	128511	Genus	12	0.22
	Telopelopia	128233	Genus	5	0.28
	Chironomidae	127917	Family	3050	8.52
Chloroperlidae	*Chloroperlidae*	103202	Family	822	2.01
	Suwallia	103254	Genus	371	1.03
	Kathroperla	103236	Genus	1	0.16
	Sweltsa	103273	Genus	3575	5.42
	Paraperla	103233	Genus	49	0.29
Clitellata	*Clitellata*	568832	Class	517	2.77
Coenagrionidae	*Coenagrionidae*	102077	Family	4	0.27
Corixidae	*Corixidae*	103364	Family	3	0.23
Crambidae	*Petrophila*	117682	Genus	3	0.23
Deuterophlebiidae	*Deuterophlebia*	121287	Genus	15	0.39
Diptera	*Agapetus*	117121	Genus	1	0.17
	Dolophilodes	115319	Genus	15	0.32
	Diptera	118831	Order	6	0.15
Dytiscidae	*Oreodytes obesus*	112314	Genus	2	0.16
	Oreodytes	112314	Genus	75	0.76
	Stictotarsus	568826	Genus	1	0.16

Table G1 (continued). Macroinvertebrate taxa list and relative abundances from Stream Ecological Integrity monitoring at Glacier National Park, 2007–2009. Total counts are followed by mean relative abundances. Macroinvertebrate taxa were identified by multiple taxonomists, so we use Operational Taxonomic Units (OTUs) to collapse identifications to comparable values. If taxa were identified at a level above family, we include this in the Family column.

Family (or higher)	Taxa (Rocky Mountain Network OTU)	Taxonomic Serial Number	Level of identification	Total count (2007–2009)	Mean relative abundance
Dytiscidae (cont'd)	*Colymbetes densus*	728325	Species	1	0.15
	Hydroporinae	678402	Subfamily	8	1.61
Elmidae	*Cleptelmis addenda*	114166	Species	14	0.47
	Optioservus quadrimaculatus	114177	Genus	10	0.27
	Ordobrevia	114235	Genus	254	2.64
	Heterlimnius	114167	Genus	1735	3.80
	Ordobrevia nubifera	114235	Genus	69	1.02
	Heterlimnius corpulentus	114167	Genus	26	1.41
	Zaitzevia	114205	Genus	606	2.11
	Narpus	114142	Genus	8	0.22
	Microcylloepus	114146	Genus	58	3.60
	Lara	114137	Genus	1	0.12
	Zaitzevia parvula	114205	Genus	16	0.32
	Optioservus	114177	Genus	524	2.38
	Stenelmis	114095	Genus	31	5.85
Empididae	*Neoplasta*	136352	Genus	94	1.02
	Clinocera	135849	Genus	32	0.52
	Chelifera	136305	Genus	84	0.60
	Hemerodromia	136327	Genus	27	0.78
	Trichoclinocera	135903	Genus	1	0.17
	Oreogeton	136377	Genus	15	0.48
	Wiedemannia	135920	Genus	41	0.49
Enchytraeidae	*Fridericia*	68510	Family	1	0.15
Ephemerellidae	*Serratella*	101395	Genus	183	1.52
	Ephemerella aurivillii	101255	Species	12	1.94
	Serratella tibialis	101399	Species	242	1.17
	Caudatella hystrix	101348	Species	20	0.63
	Caudatella	101347	Genus	34	0.37
	Ephemerella	101233	Genus	1700	4.60
	Timpanoga hecuba	101318	Species	44	0.84
	Ephemerella inermis	101239	Species	448	5.58
	Ephemerellidae	101232	Family	282	2.07
	Timpanoga	101318	Species	2	0.19
Ephemeridae	*Ephemera simulans*	101530	Species	85	6.94
	Ephemera	101526	Genus	66	3.60
Ephemeroptera	*Ephemeroptera*	100502	Order	10	0.41
	Doroneuria	103121	Genus	84	0.69
	Agraylea	115635	Genus	13	0.43
Erpobdellidae	*Erpobdellidae*	69438	Family	2	0.34
Gastropoda	*Doroneuria theodora*	103121	Genus	16	0.52
	Gastropoda	69459	Class	3	0.12
	Alloperla	103203	Genus	7	1.14

Table G1 (continued). Macroinvertebrate taxa list and relative abundances from Stream Ecological Integrity monitoring at Glacier National Park, 2007–2009. Total counts are followed by mean relative abundances. Macroinvertebrate taxa were identified by multiple taxonomists, so we use Operational Taxonomic Units (OTUs) to collapse identifications to comparable values. If taxa were identified at a level above family, we include this in the Family column.

Family (or higher)	Taxa (Rocky Mountain Network OTU)	Taxonomic Serial Number	Level of identification	Total count (2007–2009)	Mean relative abundance
Gerridae	*Gerridae*	103801	Family	1	0.16
Glossiphoniidae	*Glossiphoniidae*	69357	Family	4	0.33
Glossosomatidae	*Glossosoma*	117159	Genus	496	1.62
	Glossosomatidae	117120	Family	68	0.53
Gomphidae	*Ophiogomphus*	101738	Genus	69	1.31
	Gomphidae	101664	Family	16	0.64
Haliplidae	*Haliplus*	111858	Genus	1	0.15
Haplotaxidae	*Haplotaxis*	68505	Genus	1	0.15
Helicopsychidae	*Helicopsyche*	117016	Genus	53	3.96
Helodon	*Drunella*	101365	Genus	143	1.20
	Ambrysus	103614	Genus	2	0.38
Heptageniidae	*Heptageniidae*	100504	Family	3970	6.57
	Rhithrogena	100572	Genus	3939	6.86
	Maccaffertium	697957	Genus	19	1.61
	Nixe	100692	Genus	4	0.32
	Cinygma	100598	Genus	4	0.20
	Cinygmula	100557	Genus	1856	4.22
	Epeorus longimanus	100637	Species	231	1.55
Hyalellidae	*Hyalella*	94025	Genus	4	0.20
Hydracarina	*Hydracarina*	–	Clade	7	1.41
	Drunella coloradensis	101389	Species	340	1.44
	Ameletus	100996	Genus	1369	2.59
Hydrachna	*Hydrachna*	733321	Subclass	2	0.37
	Drunella doddsii	698494	Species	1805	3.06
	Amphicosmoecus canax	116254	Species	2	0.12
Hydraenidae	*Hydraena pacifica*	112760	Species	2	0.33
Hydridae	*Hydra*	50845	Genus	4	0.63
Hydrophilidae	*Hydrophilidae*	112811	Family	1	0.08
Hydropsychidae	*Cheumatopsyche*	115408	Genus	573	6.61
	Ceratopsyche	115453	Genus	4	0.75
	Parapsyche elsis	115560	Species	49	0.40
	Parapsyche	115556	Genus	26	0.35
	Hydropsychidae	115398	Family	598	1.68
	Hydropsyche Morosa Gr.	115453	Genus	15	0.82
	Hydropsyche	115453	Genus	1147	4.13
Hydroptilidae	*Hydroptilidae*	115629	Family	10	0.21
	Ithytrichia	115823	Genus	2	0.38
	Hydroptila	115641	Genus	101	1.13
	Mayatrichia	115811	Genus	1	0.19
	Ochrotrichia	115714	Genus	1	0.16
Hydrozetes	*Drunella flavilinea*	101392	Species	78	1.00
	Hydrozetes	733321	Subclass	1	0.17

Table G1 (continued). Macroinvertebrate taxa list and relative abundances from Stream Ecological Integrity monitoring at Glacier National Park, 2007–2009. Total counts are followed by mean relative abundances. Macroinvertebrate taxa were identified by multiple taxonomists, so we use Operational Taxonomic Units (OTUs) to collapse identifications to comparable values. If taxa were identified at a level above family, we include this in the Family column.

Family (or higher)	Taxa (Rocky Mountain Network OTU)	Taxonomic Serial Number	Level of identification	Total count (2007–2009)	Mean relative abundance
Hydrozetes (cont'd)	*Amphinemura*	102540	Genus	3	0.56
Hygrobates	*Drunella grandis*	101370	Species	73	0.54
	Anagapetus	117154	Genus	14	0.86
	Hygrobates	733321	Subclass	6	0.48
Hygrobatidae	*Drunella spinifera*	101385	Species	12	0.39
	Ancylidae	76568	Family	1	0.17
	Hygrobatidae	733321	Subclass	16	1.06
Lebertia	*Antocha*	119656	Genus	69	0.33
	Dubiraphia	114126	Genus	33	1.54
	Lebertia	733321	Subclass	38	0.37
Lebertiidae	*Dytiscidae*	111963	Family	51	0.46
	Lebertiidae	733321	Subclass	13	1.24
	Antocha monticola	119656	Genus	24	0.48
Lepidostomatidae	*Lepidostoma*	116794	Genus	2191	4.41
Leptoceridae	*Ceraclea*	116684	Genus	2	0.17
	Oecetis	116607	Genus	37	0.65
	Oecetis avara	116607	Genus	3	0.50
	Leptoceridae	116547	Family	3	0.28
	Nectopsyche	116651	Genus	63	3.33
Leptohyphidae	*Tricorythodes*	101405	Genus	282	5.68
Leptophlebiidae	*Paraleptophlebia*	101187	Genus	972	2.43
	Paraleptophlebia bicornuta	101206	Species	32	0.79
	Neochoroterpes	568558	Genus	160	13.59
	Leptophlebiidae	101095	Family	105	0.86
Leuctridae	*Paraleuctra*	102887	Genus	14	0.35
	Despaxia augusta	102842	Species	48	0.65
	Leuctridae	102840	Family	191	0.92
Limnephilidae	*Dicosmoecus atripes*	116266	Species	5	0.16
	Chyrandra centralis	116018	Species	5	0.20
	Psychoglypha	115974	Genus	15	0.33
	Limnephilidae	115933	Family	136	0.86
	Onocosmoecus unicolor	116318	Species	5	0.19
	Dicosmoecus	116265	Genus	12	0.33
	Homophylax	116286	Genus	1	0.16
Lumbriculidae	*Lumbriculus*	68441	Genus	1	0.10
	Rhynchelmis	68463	Genus	53	0.60
	Lumbriculidae	68440	Family	152	2.34
Lymnaeidae	*Lymnaeidae*	76483	Family	2	0.14
	Stagnicola	76534	Genus	4	0.66
Muscidae	*Muscidae*	150025	Family	1	0.15
Naididae	*Nais*	68946	Genus	437	3.22

Table G1 (continued). Macroinvertebrate taxa list and relative abundances from Stream Ecological Integrity monitoring at Glacier National Park, 2007–2009. Total counts are followed by mean relative abundances. Macroinvertebrate taxa were identified by multiple taxonomists, so we use Operational Taxonomic Units (OTUs) to collapse identifications to comparable values. If taxa were identified at a level above family, we include this in the Family column.

Family (or higher)	Taxa (Rocky Mountain Network OTU)	Taxonomic Serial Number	Level of identification	Total count (2007–2009)	Mean relative abundance
Naididae (cont'd)	*Chaetogaster*	68934	Genus	10	0.56
	Slavina	68855	Genus	1	0.16
	Naididae	68854	Family	2	0.38
Nemata	*Nemata*	59490	Phylum	1	0.19
	Ecclisomyia	116025	Genus	34	0.37
	Apatania	115935	Genus	219	1.05
Nematoda	*Apsectrotanypus*	128021	Genus	3	0.34
	Nematoda	59490	Phylum	68	0.60
	Eclipidrilus	68473	Genus	9	0.35
Nemouridae	*Zapada*	102591	Genus	486	1.68
	Malenka	102567	Genus	19	0.39
	Zapada Oregonensis Gr.	102597	Group	98	1.07
	Zapada columbiana	102596	Species	523	2.30
	Nemouridae	102517	Family	135	1.36
	Visoka cataractae	102615	Species	55	0.53
	Zapada frigida	102601	Species	3	0.18
	Zapada cinctipes	102594	Species	189	1.35
	Prostoia	102584	Genus	68	3.30
Ostracoda	*Arctopsyche*	115529	Genus	305	1.39
	Elmidae	114093	Family	573	1.53
	Ostracoda	84195	Class	82	0.95
Pelecorhynchidae	*Glutops*	130915	Genus	116	0.65
Peltoperlidae	*Yoraperla*	102510	Genus	6	0.25
	Yoraperla brevis	102512	Species	54	0.76
Perlidae	*Hesperoperla*	102972	Species	6	1.11
	Claassenia sabulosa	102932	Species	63	0.54
	Calineuria californica	102986	Species	74	0.51
	Perlidae	102914	Family	335	0.89
	Hesperoperla pacifica	102972	Species	84	0.54
Perlodidae	*Kogotus*	103149	Genus	4	0.16
	Isogenoides	103124	Genus	2	0.16
	Megarcys	103110	Genus	247	1.05
	Setvena	103193	Genus	2	0.12
	Skwala	103102	Genus	21	0.35
	Isoperla	102995	Genus	24	0.38
	Perlodidae	102994	Family	451	0.90
Philopotamidae	*Wormaldia*	115258	Genus	14	2.20
	Philopotamidae	115257	Family	1	0.09
Phoridae	*Phoridae*	138921	Family	3	0.16
Physidae	*Physa*	76677	Genus	23	0.37
Pionidae	*Pionidae*	733321	Subclass	3	0.60
	Arctopsyche grandis	115530	Species	104	0.68

Table G1 (continued). Macroinvertebrate taxa list and relative abundances from Stream Ecological Integrity monitoring at Glacier National Park, 2007–2009. Total counts are followed by mean relative abundances. Macroinvertebrate taxa were identified by multiple taxonomists, so we use Operational Taxonomic Units (OTUs) to collapse identifications to comparable values. If taxa were identified at a level above family, we include this in the Family column.

Family (or higher)	Taxa (Rocky Mountain Network OTU)	Taxonomic Serial Number	Level of identification	Total count (2007–2009)	Mean relative abundance
Pionidae (cont'd)	*Empididae*	135830	Family	134	0.48
Piscicolidae	*Piscicola*	69304	Genus	1	0.18
Pisidiidae	*Sphaerium*	81391	Genus	18	3.03
	Pisidium	81400	Genus	165	1.10
Planariidae	*Polycelis coronata*	54512	Species	205	0.96
Planorbidae	*Gyraulus*	76592	Genus	45	0.70
	Helisoma	76599	Genus	2	0.34
	Promenetus	76621	Genus	11	0.80
	Planorbidae	76591	Family	2	0.16
Plecoptera	*Plecoptera*	102467	Order	164	0.85
	Atherix	130929	Genus	214	0.96
	Enchytraeidae	68510	Family	37	0.47
Polycentropodidae	*Polycentropodidae*	117043	Family	1	0.10
Polymitarcyidae	*Ephoron*	101570	Genus	4	0.75
Protzia	*Protzia*	733321	Subclass	17	0.28
	Enchytraeus	68510	Family	39	0.93
Psychodidae	*Pericoma*	125514	Genus	683	3.39
	Psychodidae	125351	Family	24	0.64
Pteronarcyidae	*Pteronarcys californica*	102473	Species	43	0.39
	Pteronarcella	102485	Genus	5	0.16
	Pteronarcella badia	102486	Species	2	0.15
	Pteronarcys	102471	Genus	7	0.27
Rhyacophilidae	*Rhyacophila Brunnea Gr.*	115151	Group	71	0.49
	Rhyacophila Vofixa Gr.	115197	Group	7	0.22
	Rhyacophila verrula	115125	Species	6	0.29
	Rhyacophila Vagrita Gr.	115152	Group	28	0.54
	Rhyacophila pellisa	115114	Species	38	0.44
	Rhyacophila oreia	115208	Species	2	0.24
	Rhyacophila Hyalinata Gr.	115159	Group	107	0.70
	Rhyacophila Betteni Gr.	115101	Group	220	1.00
	Rhyacophila arnaudi	115165	Species	3	0.32
	Rhyacophila Angelita Gr.	115099	Group	13	0.45
	Rhyacophila Alberta Gr.	115163	Group	9	0.28
	Rhyacophila	115097	Genus	487	0.92
	Rhyacophila narvae	115155	Species	84	0.60
Sialidae	*Sialis*	115002	Genus	20	0.55
Simuliidae	*Helodon*	–	Genus	17	0.91
	Simulium	126774	Genus	1270	4.41
	Prosimulium	126703	Genus	14	0.54
	Simuliidae	126640	Family	1802	4.15
Siphlonuridae	*Siphlonurus*	100953	Genus	22	1.25
Sperchon	*Attenella*	101338	Genus	5	0.38

Table G2. Diatom species list and relative abundances from Stream Ecological Integrity monitoring at Glacier National Park, 2007–2009. Diatom taxa were identified using a consistent nomenclature.

Taxa	Taxonomic Serial Number	Total count (2007–2010)	Mean relative abundance
Achnanthes biasolettiana v. *subatomus*	-633455	12	1.72
Achnanthes catenata	-633476	3	0.50
Achnanthes clevei v. *bottnica*	-633481	1	0.15
Achnanthes conspicua	3445	2	0.30
Achnanthes curtissima	-633490	2	0.28
Achnanthes linearis	3516	1	0.35
Achnanthes minutissima v. *jackii*	-633608	40	0.54
Achnanthes nodosa	3567	10.5	0.41
Achnanthes petersenii	-633638	8	0.53
Achnanthes rosenstockii	-633663	8	0.28
Achnanthes rossii	193781	0.5	0.07
Achnanthes sp.	3429	2	0.23
Achnanthes subhudsonis	3559	14	2.33
Achnanthidium affine	591149	24	0.66
Achnanthidium catenatum	–	14	1.17
Achnanthidium deflexum	-633710	574.5	1.74
Achnanthidium duthii	591150	0.5	0.08
Achnanthidium exiguum	591151	1	0.17
Achnanthidium exilis	591152	2	0.33
Achnanthidium gracillimum	–	1778.5	5.04
Achnanthidium microcephalum	591165	10	1.55
Achnanthidium minutissimum	591164	19545	27.06
Achnanthidium minutissimum v. *jackii*	–	23	0.70
Achnanthidium neomicrocephalum	–	677.5	4.38
Achnanthidium pyrenaicum	-633732	4921.5	10.15
Achnanthidium rivulare	–	60.5	0.52
Achnanthidium sp.	590864	4	0.59
Adlafia bryophila	-633770	22	0.63
Adlafia minuscula	-633773	116.5	0.68
Adlafia suchlandtii	-633777	40	0.65
Amphipleura pellucida	4580	205.5	0.78
Amphora copulata	-633872	9	0.19
Amphora inariensis	591196	13	0.32
Amphora ovalis	4721	1	0.15
Amphora pediculus	-633945	40	0.40
Amphora sp.	4705	1	0.14
Amphora veneta	4739	0.5	0.08
Asterionella formosa	3120	18	0.48
Aulacoseira	590863	2	0.33
Aulacoseira alpigena	591204	39	0.53
Aulacoseira ambigua	591194	1	0.17
Aulacoseira canadensis	591195	2	0.15
Aulacoseira crenulata	591483	14	1.16
Aulacoseira distans	591208	2	0.15

Table G2 (continued). Diatom species list and relative abundances from Stream Ecological Integrity monitoring at Glacier National Park, 2007–2009. Diatom taxa were identified using a consistent nomenclature.

Taxa	Taxonomic Serial Number	Total count (2007–2010)	Mean relative abundance
Aulacoseira italica	591483	27.5	0.45
Aulacoseira sp.	590863	8	0.29
Brachysira microcephala	-634189	507	2.35
Brachysira serians	591203	2	0.33
Brachysira sp.	590866	23	3.85
Brachysira vitrea	591201	16	0.90
Caloneis	4369	0.5	0.08
Caloneis bacillum	4382	63.5	0.60
Caloneis schumanniana	4392	3	0.21
Caloneis silicula	4393	21	0.26
Caloneis sp.	4369	6	0.32
Caloneis tenuis	193803	10.5	0.37
Caloneis undulata	591179	2.5	0.18
Cavinula cocconeiformis	591188	15.5	0.33
Cavinula pseudoscutiformis	591184	5.5	0.23
Chamaepinnularia sp.	590860	2	0.30
Cocconeis pediculus	3617	3.5	0.19
Cocconeis placentula	3596	1159.5	1.89
Craticula ambigua	591123	2	0.14
Craticula buderi	-634549	3	0.23
Craticula cuspidata	591122	0.5	0.08
Cyclostephanos costatilimbus	591107	2	0.29
Cyclotella	2439	0.5	0.08
Cyclotella antiqua	2459	0.5	0.08
Cyclotella comensis	2464	39	0.44
Cyclotella distinguenda	591103	1	0.07
Cyclotella glomerata	2470	3	0.22
Cyclotella meneghiniana	2445	12	1.67
Cyclotella michiganiana	2471	6	0.22
Cyclotella ocellata	2472	22.5	0.56
Cyclotella pseudostelligera	2481	160.5	1.70
Cyclotella sp.	2439	1	0.16
Cylindrotheca closterium	5318	2	0.32
Cymatopleura elliptica	3259	1.5	0.07
Cymatopleura solea	3262	4.5	0.07
Cymbella affinis	4803	4	0.68
Cymbella alpestris	-634616	0.5	0.08
Cymbella aspera	4810	2	0.11
Cymbella cistula	4816	4.5	0.25
Cymbella cymbiformis	4893	2.5	0.19
Cymbella delicatula	4824	328	1.96
Cymbella excisa	–	679.5	2.04
Cymbella excisiformis	-634677	331	1.56
Cymbella hebridica	4831	7	1.17

Table G2 (continued). Diatom species list and relative abundances from Stream Ecological Integrity monitoring at Glacier National Park, 2007–2009. Diatom taxa were identified using a consistent nomenclature.

Taxa	Taxonomic Serial Number	Total count (2007–2010)	Mean relative abundance
Cymbella hustedtii	4832	6	0.31
Cymbella laevis	4835	8	0.40
Cymbella lanceolata	4836	2.5	0.18
Cymbella maggiana	-634745	4.5	0.35
Cymbella mexicana	4843	3	0.09
Cymbella naviculiformis	4852	1	0.16
Cymbella neocistula	-634758	91	0.42
Cymbella neoleptoceros	-634761	4	0.31
Cymbella perparva	-634788	174.5	1.72
Cymbella proxima	4890	0.5	0.08
Cymbella pusilla	4860	2	0.30
Cymbella rumrichae	-634802	106.5	1.65
Cymbella sp.	4795	25.5	0.52
Cymbella sp. 398401 GLAC LLB	4795	0.5	0.08
Cymbella sp. 409701 GLAC LLB	4795	3	0.46
Cymbella subturgidula	-634839	208	3.13
Cymbella vulgata	-634873	2	0.32
Cymbopleura amphicephala	–	5	0.19
Cymbopleura apiculata	–	0.5	0.07
Cymbopleura frequens	–	2	0.30
Cymbopleura heinii	-634896	0.5	0.07
Cymbopleura inaequalis	–	0.5	0.08
Cymbopleura naviculiformis	–	7.5	0.18
Cymbopleura rupicola	–	0.5	0.08
Cymbopleura sp.	–	2	0.71
Cymbopleura subaequalis	–	16.5	0.32
Cymbopleura subcuspidata	–	4.5	0.13
Cymbopleura subrostrata	–	1.5	0.08
Denticula elegans	5322	4	0.67
Denticula kuetzingii	-634929	26	0.46
Denticula sp.	5319	2	0.33
Denticula tenuis	5326	99	0.58
Diadesmis perpusilla	591217	10	0.23
Diatoma anceps	3226	72	2.34
Diatoma hiemalis	–	72	0.58
Diatoma mesodon	193761	652.5	1.57
Diatoma moniliformis	–	109	1.79
Diatoma tenuis	–	800	3.48
Diatoma vulgaris	–	2	0.33
Diatomella balfouriana	3331	23	0.74
Didymosphenia geminata	591283	126.5	0.23
Diploneis alpina	-635020	0.5	0.08
Diploneis marginestriata	193802	2	0.29
Diploneis oblongella	4360	4	0.31

Table G2 (continued). Diatom species list and relative abundances from Stream Ecological Integrity monitoring at Glacier National Park, 2007–2009. Diatom taxa were identified using a consistent nomenclature.

Taxa	Taxonomic Serial Number	Total count (2007–2010)	Mean relative abundance
Diploneis ovalis	4357	9	0.23
Diploneis puella	4335	1	0.16
Distrionella incognita	–	143	1.37
Encyonema	590838	1	0.17
Encyonema cespitosum	591280	30.5	0.41
Encyonema elginense	-635153	4	0.39
Encyonema evergladianum	-635155	8	0.59
Encyonema fogedii	-635156	2	0.31
Encyonema gaeumannii	–	2	0.28
Encyonema hebridicum	591282	9.5	0.47
Encyonema kamtschaticum	-635184	1	0.14
Encyonema lange-bertalotii	-635189	20	1.62
Encyonema latens	591286	5	0.80
Encyonema lunatum	591267	1	0.15
Encyonema minutum	591268	622	1.31
Encyonema muelleri	591269	17	0.19
Encyonema neogracile	-635214	15	0.24
Encyonema perminutum	-635234	2	0.33
Encyonema prostratum	591266	2	0.07
Encyonema reichardtii	-635244	40.5	0.50
Encyonema silesiacum	591272	3869.5	5.54
Encyonema sp.	590838	7	0.27
Encyonema sp. 050803 GLAC LLB	590838	0.5	0.07
Encyonema ventricosum	591277	95	0.73
Encyonema vulgare	-635304	3	0.43
Encyonopsis cesatiformis	–	6	1.02
Encyonopsis cesatii	–	163.5	0.83
Encyonopsis descripta	–	35	0.56
Encyonopsis falaisensis	–	10	0.83
Encyonopsis krammeri	–	10	0.84
Encyonopsis microcephala	–	482	2.41
Encyonopsis minuta	–	8	0.68
Encyonopsis perborealis	–	207	3.90
Encyonopsis sp.	–	52	2.15
Encyonopsis subminuta	–	1018	2.67
Eolimna minima	-635334	246	0.83
Epithemia adnata	591291	32.5	0.54
Epithemia argus	5006	11	1.71
Epithemia sorex	5019	90.5	1.11
Epithemia turgida	5020	45.5	0.30
Eucocconeis alpestris	-635377	1	0.14
Eucocconeis flexella	591226	75.5	0.40
Eucocconeis laevis	-635382	162	0.59
Eunotia bilunaris	-635424	11	0.41

Table G2 (continued). Diatom species list and relative abundances from Stream Ecological Integrity monitoring at Glacier National Park, 2007–2009. Diatom taxa were identified using a consistent nomenclature.

Taxa	Taxonomic Serial Number	Total count (2007–2010)	Mean relative abundance
Eunotia diadema	-635474	3	0.50
Eunotia diodon	3344	11	1.82
Eunotia exigua	3348	2.5	0.19
Eunotia glacialis	3353	2	0.33
Eunotia implicata	-635535	7.5	0.29
Eunotia incisa	3379	1	0.15
Eunotia minor	193765	26	0.39
Eunotia monodon	3405	1	0.35
Eunotia muscicola v. *tridentula*	-635584	2	0.46
Eunotia paludosa	193762	1	0.17
Eunotia praerupta	3365	4	0.15
Eunotia praerupta v. *bidens*	3342	0.5	0.07
Eunotia sp.	3337	27	0.63
Fallacia subhamulata	591218	0.5	0.08
Fallacia tenera	-635814	4	0.66
Fragilaria capucina	2953	179	0.76
Fragilaria capucina v. *gracilis*	–	4	0.33
Fragilaria capucina v. *mesolepta*	2956	4	0.68
Fragilaria capucina v. *perminuta*	–	4	0.68
Fragilaria crotonensis	2933	64.5	0.76
Fragilaria oldenburgiana	–	2	0.29
Fragilaria sepes	–	401.5	2.13
Fragilaria sp.	2932	103	5.69
Fragilaria tenera	–	276.5	1.62
Fragilaria vaucheriae	2942	224	3.10
Fragilaria vaucheriae morphotype A GLAC LLB	2942	1409.5	2.40
Fragilaria vaucheriae morphotype B GLAC LLB	2942	903.5	3.38
Fragilaria vaucheriae v. *capitellata*	2945	62.5	0.68
Fragilariforma bicapitata	591231	9	0.33
Fragilariforma sp. 1 NAWQA EAM	590826	4	0.61
Frustulia amphipleuroides	-635860	4.5	0.15
Frustulia crassinervia	-635873	6	0.47
Frustulia erifuga	591252	0.5	0.08
Frustulia krammeri	-635895	4	0.09
Frustulia saxonica	591253	1	0.17
Frustulia sp.	4564	1	0.16
Frustulia vulgaris	4571	7.5	0.16
Geissleria acceptata	591255	9	0.45
Geissleria decussis	591256	10	0.39
Gomphoneis eriense	4987	38	0.64
Gomphoneis geitleri	591262	330	1.79
Gomphoneis mammilla	-636024	0.5	0.08
Gomphoneis minuta	–	1	0.08
Gomphoneis olivaceoides	-636026	1735	4.08

Table G2 (continued). Diatom species list and relative abundances from Stream Ecological Integrity monitoring at Glacier National Park, 2007–2009. Diatom taxa were identified using a consistent nomenclature.

Taxa	Taxonomic Serial Number	Total count (2007–2010)	Mean relative abundance
Gomphoneis olivaceum	-636027	19	1.04
Gomphoneis septa	-636030	15.5	0.46
Gomphoneis sp.	4912	2	0.27
Gomphonema	4911	4	0.66
Gomphonema acidoclinatum	–	6	0.86
Gomphonema acuminatum	4919	16.5	0.77
Gomphonema aff. *longilineare* GLAC LLB	-636027	752	2.36
Gomphonema affine	4956	2	0.28
Gomphonema americobtusatum	-636042	7	0.24
Gomphonema angustatum	4927	277.5	4.20
Gomphonema angustivalva	-636048	1	0.16
Gomphonema auritum	-636061	13	0.98
Gomphonema bipunctatum	-636065	2	0.28
Gomphonema brebissonii	-636071	0.5	0.08
Gomphonema capitatum	591020	10	0.71
Gomphonema cf. *minutum* GLAC LLB	4911	200.5	1.76
Gomphonema cf. *pumilum* GLAC LLB	4911	275	2.07
Gomphonema citera	–	1728.5	4.78
Gomphonema clavatulum	-636084	0.5	0.07
Gomphonema cymbelliclinum	-636100	8	0.58
Gomphonema exilissimum	-636115	0.5	0.07
Gomphonema gracile	4941	3.5	0.29
Gomphonema instabilis	–	3	0.24
Gomphonema intricatum	4949	18	0.41
Gomphonema longilineare	-636164	5	0.40
Gomphonema micropus	-636175	22	0.35
Gomphonema minusculum	-636177	512	4.87
Gomphonema minutum	-636179	191	1.76
Gomphonema olivaceoides	4961	376.5	3.61
Gomphonema olivaceum	4971	24	1.32
Gomphonema olivaceum v. *minutissimum*	-636199	21.5	0.79
Gomphonema pala	-636208	0.5	0.08
Gomphonema paludosum	-636209	6.5	0.49
Gomphonema parvulum	4975	52.5	0.52
Gomphonema procerum	-636228	0.5	0.07
Gomphonema pseudotenellum	591244	6	1.02
Gomphonema pumilum	-636234	1405	3.13
Gomphonema pygmaeum	591245	244	1.90
Gomphonema quadripunctatum	4981	1	0.16
Gomphonema rhombicum	-636243	12	0.66
Gomphonema sarcophagus	591144	0.5	0.08
Gomphonema sp.	4911	160	0.87
Gomphonema sp. 408603 GLAC LLB	4911	29	1.37
Gomphonema sp. 408705 GLAC LLB	4911	2	0.26

Table G2 (continued). Diatom species list and relative abundances from Stream Ecological Integrity monitoring at Glacier National Park, 2007–2009. Diatom taxa were identified using a consistent nomenclature.

Taxa	Taxonomic Serial Number	Total count (2007–2010)	Mean relative abundance
Gomphonema sp. 408801 GLAC LLB	4911	0.5	0.08
Gomphonema sp. 409801 GLAC LLB	4911	5	0.77
Gomphonema sp. 437501 GLAC LLB	4911	30	4.56
Gomphonema subclavatum	4968	13.5	0.27
Gomphonema truncatum	193820	7	0.35
Gomphonema utae	-636280	1	0.17
Gomphosphenia sp.	–	129	2.10
Gyrosigma acuminatum	4633	1	0.07
Gyrosigma scalproides	4640	0.5	0.07
Hannaea arcus	3322	3786	7.10
Hantzschia amphioxys	5304	6	0.24
Hantzschia sp.	5303	6.5	0.24
Hippodonta capitata	591473	2	0.30
Hippodonta hungarica	591437	5	0.72
Karayevia clevei	591430	2	0.27
Karayevia laterostrata	591429	3	0.22
Karayevia suchlandtii	–	1	0.16
Luticola	590847	0.5	0.08
Luticola nivalis	-636601	1	0.14
Luticola sp.	590847	1	0.15
Mastogloia smithii	4553	0.5	0.08
Mayamaea atomus	-636725	14	0.35
Melosira varians	2339	53	0.63
Meridion circulare	3238	252	0.79
Meridion circulare v. *constrictum*	3240	2	0.33
Navicula	3649	0.5	0.08
Navicula angusta	3824	2	0.28
Navicula antonii	-636836	132	0.81
Navicula aquaedurae	-636844	2	0.30
Navicula arctotenelloides	-636847	152	0.64
Navicula associata	-636860	2.5	0.19
Navicula aurora	3812	5.5	0.09
Navicula bryophila	3818	1	0.14
Navicula capitatoradiata	591359	17.5	0.30
Navicula catalanogermanica	-636947	2	0.32
Navicula caterva	-636950	0.5	0.08
Navicula cf. *wildii* GLAC LLB	3649	7	0.33
Navicula constans	3833	0.5	0.07
Navicula cryptocephala	3662	170.5	0.65
Navicula cryptofallax	-637009	49	2.34
Navicula cryptotenella	591338	365	0.83
Navicula detenta	591340	3	0.22
Navicula disjuncta	4055	0.5	0.08
Navicula eidrigiana	-637089	0.5	0.08

Table G2 (continued). Diatom species list and relative abundances from Stream Ecological Integrity monitoring at Glacier National Park, 2007–2009. Diatom taxa were identified using a consistent nomenclature.

Taxa	Taxonomic Serial Number	Total count (2007–2010)	Mean relative abundance
Navicula exilis	590937	2	0.34
Navicula glomus	-637181	3	0.15
Navicula gregaria	3860	96	1.28
Navicula helensis	4026	2	0.29
Navicula hintzii	-637220	20	0.40
Navicula krammerae	-637290	7.5	0.23
Navicula laterostrata	3884	0.5	0.08
Navicula lundii	-637340	12.5	0.30
Navicula minima	3889	2	0.33
Navicula modica	193791	0.5	0.08
Navicula moskalii	-637405	8	0.59
Navicula muralis	3726	1	0.15
Navicula notha	3908	1.5	0.12
Navicula oligotraphenta	-637453	5	0.36
Navicula oppugnata	3913	4	0.31
Navicula pseudosilicula f. olympica	–	0.5	0.08
Navicula pseudoventralis	3941	7	0.34
Navicula radiosa	3952	119.5	0.42
Navicula radiosafallax	591351	2	0.33
Navicula reichardtiana	-637579	262	2.49
Navicula rhynchocephala	3678	14	0.23
Navicula semen	4073	0.5	0.08
Navicula seminuloides	3973	2	0.28
Navicula sp.	3649	21	0.29
Navicula sp. 404201 GLAC LLB	3649	1	0.07
Navicula stroemii	3982	21.5	0.40
Navicula subadnata	-637697	0.5	0.07
Navicula subalpina	-637698	8	0.29
Navicula subconcentrica	-637701	2	0.30
Navicula subrotundata	3990	2	0.31
Navicula tantula	3995	2	0.33
Navicula tripunctata	4048	11.5	0.34
Navicula trivialis	-637759	3	0.11
Navicula vaucheriae	4008	2	0.28
Navicula ventralis	4010	8	0.62
Navicula viridula	4013	4	0.20
Navicula viridulacalcis	-637813	5.5	0.17
Navicula vitabunda	4017	2	0.32
Navicula vulpina	4021	5	0.19
Navicula wildii	-637826	2	0.29
Naviculadicta ventraloconfusa	-637875	5.5	0.21
Neidiopsis wulfii	–	1	0.07
Neidium affine	3270	1	0.08
Neidium ampliatum	591304	3.5	0.10

Table G2 (continued). Diatom species list and relative abundances from Stream Ecological Integrity monitoring at Glacier National Park, 2007–2009. Diatom taxa were identified using a consistent nomenclature.

Taxa	Taxonomic Serial Number	Total count (2007–2010)	Mean relative abundance
Neidium binodeformis	–	0.5	0.07
Neidium bisulcatum	3285	2.5	0.18
Neidium dubium	3291	2.5	0.18
Neidium ladogensis	-637957	0.5	0.08
Neidium productum	3310	2	0.28
Neidium sp.	3269	4	0.30
Nitzschia	5070	1	0.17
Nitzschia acicularioides	5217	4	0.30
Nitzschia acicularis	5099	16.5	0.32
Nitzschia agnita	591327	8	1.33
Nitzschia alpina	-637997	34	0.47
Nitzschia amphibia	5160	17	0.34
Nitzschia amphibia f. frauenfeldii	-638003	6	0.29
Nitzschia angustata	5265	57.5	0.31
Nitzschia angustatula	591322	5	0.37
Nitzschia archibaldii	591312	89.5	0.92
Nitzschia bacillum	-638030	134.5	1.15
Nitzschia bryophila	-638047	272.5	1.03
Nitzschia communis	5223	2	0.31
Nitzschia dissipata	5186	657	1.55
Nitzschia dissipata v. *media*	5188	2	0.33
Nitzschia draveillensis	591355	4	0.63
Nitzschia fonticola	5198	56	1.15
Nitzschia fossilis	-638099	1	0.15
Nitzschia frustulum	5150	32.5	0.77
Nitzschia graciliformis	591448	14	0.34
Nitzschia gracilis	5234	27.5	0.39
Nitzschia heufleriana	591451	18	0.19
Nitzschia homburgiensis	591453	6	0.95
Nitzschia incognita	-638122	3	0.23
Nitzschia inconspicua	193822	14	0.44
Nitzschia intermedia	5242	3.5	0.11
Nitzschia lacuum	591426	57	0.68
Nitzschia lancettula	–	23	0.35
Nitzschia linearis	5104	194	0.87
Nitzschia palea	5208	101.5	0.56
Nitzschia paleacea	5250	204	1.36
Nitzschia perminuta	193823	450	1.37
Nitzschia pumila	591476	6	1.00
Nitzschia pura	591475	326	0.82
Nitzschia pusilla	591471	18	0.38
Nitzschia radicula	591474	11	0.52
Nitzschia recta	5195	65.5	0.37
Nitzschia sigmoidea	5127	2.5	0.12

Table G2 (continued). Diatom species list and relative abundances from Stream Ecological Integrity monitoring at Glacier National Park, 2007–2009. Diatom taxa were identified using a consistent nomenclature.

Taxa	Taxonomic Serial Number	Total count (2007–2010)	Mean relative abundance
Nitzschia sinuata	5254	1	0.14
Nitzschia sinuata v. *tabellaria*	5256	2	0.14
Nitzschia sp.	5070	15	0.39
Nitzschia subacicularis	5259	8.5	0.24
Nitzschia sublinearis	5261	7.5	0.37
Nitzschia subtilis	5278	25	0.46
Nitzschia subvitrea	–	0.5	0.08
Nitzschia vermicularis	5135	27	0.37
Nupela lapidosa	-638351	14	0.44
Nupela sp.	–	3	0.43
Parlibellus protracta	-638401	2	0.28
Pinnularia	4428	0.5	0.08
Pinnularia acuminata	-638446	0.5	0.07
Pinnularia borealis	4462	6	0.19
Pinnularia decrescens	–	0.5	0.07
Pinnularia divergens	4473	0.5	0.08
Pinnularia gibbiformis	-638617	0.5	0.07
Pinnularia interrupta	4485	0.5	0.08
Pinnularia mesogongyla v. *interrupta*	–	0.5	0.07
Pinnularia microstauron	4500	7.5	0.41
Pinnularia nodosa	4504	0.5	0.08
Pinnularia nodosa v. *percapitata*	-638764	0.5	0.08
Pinnularia obscura	4505	2	0.15
Pinnularia rhombarea	-638837	2	0.71
Pinnularia sp.	4428	20.5	0.31
Pinnularia sp. 435902 GLAC LLB	4428	0.5	0.07
Pinnularia subcapitata	4509	0.5	0.08
Pinnularia viridis	4440	1	0.16
Placoneis elginensis	591406	3.5	0.13
Placoneis explanata	-639008	0.5	0.08
Planothidium	590854	1	0.16
Planothidium dubium	591400	16.5	0.36
Planothidium frequentissimum	-639076	412	1.81
Planothidium haynaldii	-639083	2.5	0.19
Planothidium joursacense	-639091	1	0.16
Planothidium lanceolatoide	–	1	0.16
Planothidium lanceolatum	591421	369.5	2.20
Planothidium rostratum	590854	0.5	0.08
Planothidium sp.	590854	1	0.15
Psammothidium bioretii	-639257	16	0.30
Psammothidium chlidanos	-639261	10	0.47
Psammothidium daonense	-639264	70.5	0.71
Psammothidium levanderi	591412	2	0.27
Psammothidium sp.	590852	9	0.33
Psammothidium subatomoides	591424	30.5	0.83

Table G2 (continued). Diatom species list and relative abundances from Stream Ecological Integrity monitoring at Glacier National Park, 2007–2009. Diatom taxa were identified using a consistent nomenclature.

Taxa	Taxonomic Serial Number	Total count (2007–2010)	Mean relative abundance
Psammothidium ventralis	591411	5	0.24
Pseudostaurosira brevistriata	591385	454	1.56
Pseudostaurosira brevistriata v. *inflata*	591650	44	2.98
Pseudostaurosira elliptica	–	152	1.35
Pseudostaurosira parasitica	–	7	0.93
Pseudostaurosira pseudoconstruens	–	173	1.93
Pseudostaurosira robusta	–	1	0.16
Pseudostaurosira sp.	590851	2	0.31
Pseudostaurosira sp. 404201 GLAC LLB	590851	10	1.58
Puncticulata bodanica	–	64	0.50
Puncticulata radiosa	–	2	0.29
Reimeria sinuata	193818	1434	2.25
Rhoicosphenia abbreviata	-639383	69	0.44
Rhopalodia gibba	5041	77	0.53
Rossithidium linearis	591390	2	0.30
Rossithidium pusillum	591391	18	0.29
Sellaphora alastos	-639474	0.5	0.08
Sellaphora bacillum	591395	7.5	0.36
Sellaphora laevissima	591396	2.5	0.12
Sellaphora mutata	591397	0.5	0.08
Sellaphora pupula	591302	45	0.34
Sellaphora seminulum	590950	17	0.50
Sellaphora sp.	590842	2	0.29
Sellaphora sp. 437001 GLAC LLB	590842	2	0.29
Simonsenia delognei	-639532	6	0.82
Stauroneis anceps	4147	3	0.12
Stauroneis dilatata	4316	1.5	0.14
Stauroneis fluminea	4188	0.5	0.07
Stauroneis gracilis	4193	5	0.15
Stauroneis gracilis morphotype A GLAC LLB	4127	0.5	0.08
Stauroneis gracilis morphotype B GLAC LLB	4127	0.5	0.08
Stauroneis heinii	-639602	1	0.08
Stauroneis kriegeri	4211	5.5	0.29
Stauroneis neohyalina	590945	0.5	0.08
Stauroneis pergracilis	–	0.5	0.18
Stauroneis phoenicenteron	4252	2.5	0.09
Stauroneis siberica	590972	0.5	0.07
Stauroneis smithii	4283	5	0.25
Stauroneis sp. aff. *acidoclinata*	4127	2	0.29
Stauroneis tackei	-639662	0.5	0.08
Stauroneis thermicola	4300	1	0.16
Staurosira construens	590965	298	2.52
Staurosira construens v. *binodis*	–	12	0.65
Staurosira construens v. *pumila*	–	3.5	0.19
Staurosira construens v. *venter*	591494	17	0.94

Table G2 (continued). Diatom species list and relative abundances from Stream Ecological Integrity monitoring at Glacier National Park, 2007–2009. Diatom taxa were identified using a consistent nomenclature.

Taxa	Taxonomic Serial Number	Total count (2007–2010)	Mean relative abundance
Staurosira elliptica	–	4	0.68
Staurosira sp.	590848	10	0.37
Staurosira sp. 409902 GLAC LLB	590848	3	0.47
Staurosira venter	–	462.5	1.63
Staurosirella dubia	–	10	0.55
Staurosirella lapponica	590962	15	0.77
Staurosirella leptostauron	590961	200	0.59
Staurosirella martyi	–	442	1.35
Staurosirella ovata	–	208	2.76
Staurosirella pinnata	590892	650	2.09
Staurosirella pinnata v. *intercedens*	591489	15	2.15
Staurosirella rhomboides	–	7.5	0.40
Staurosirella sp.	590855	89	1.19
Staurosirella subrobusta	–	7	0.93
Stenopterobia curvula	-639700	3.5	0.18
Stephanodiscus alpinus	2419	1.5	0.11
Surirella angusta	5394	18.5	0.31
Surirella bifrons	591053	0.5	0.07
Surirella linearis	5381	7	0.18
Surirella linearis v. *helvetica*	5383	0.5	0.07
Surirella minuta	5392	2	0.30
Surirella ovalis	5348	1	0.17
Surirella robusta	5357	0.5	0.07
Surirella sp.	5331	2	0.29
Surirella splendida	590907	1	0.16
Surirella tenera	555634	1	0.13
Synedra acus	3056	347.5	1.08
Synedra biceps	–	103.5	0.81
Synedra delicatissima	555631	14.5	0.27
Synedra famelica	3102	3	0.50
Synedra mazamaensis	3085	10.5	0.31
Synedra rumpens	3092	1539.5	2.82
Synedra sp.	3013	3	0.44
Synedra ulna	3023	465	1.25
Synedra ulna v. *contracta*	3033	11	0.57
Synedra ulna v. *ramesi*	3041	0.5	0.08
Tabellaria fenestrata	3242	4	0.68
Tabellaria flocculosa	3247	374.5	2.07
Tabellaria sp.	3241	8	1.33
unknown centric	–	6	1.00
unknown genus	–	8	0.39
unknown naviculoid	–	2	0.29
unknown pennate	–	2	0.33
Total		72354.5	**0.73**

Table G3. Soft bodied algae taxa list and relative abundances from Stream Ecological Integrity monitoring at Glacier National Park, 2007–2009. Total counts are followed by mean relative abundances.

Taxa	Taxonomic Serial Number	Total count (2007–2009)	Mean relative abundance
Amphithrix	1285	19	6.33
Anabaena	1100	172	5.34
Ankistrodesmus	5877	47	1.17
Audouinella	11630	6	1.00
Audouinella hermannii	183017	355	5.79
Batrachospermum	11665	28	4.43
Borzia	1097	11	1.83
Bulbochaete	9115	12	3.82
Calothrix	1243	637	10.58
Chamaesiphon	847	36	5.82
Chlamydomonas	–	2	0.37
Chroococcus	654	34	1.80
Closterium	7257	8	0.38
Cosmarium	7848	18	0.57
Cryptomonas	–	1	0.18
Diatoms	2287	18697	52.12
Dichothrix	1230	99	33.00
Dinobryon	1515	18	0.95
Eucapsis	812	8	2.67
Geitleribactron	–	252	13.82
Geitlerinema	–	4	1.29
Gloeocapsopsis	–	318	20.63
Gloeothece	703	187	6.48
Gomphosphaeria	714	24	6.98
Hazenia mirabilis	-643496	35	10.77
Heribaudiella fluviatilis	–	769	11.11
Heteroleibleinia	–	797	6.66
Homeothrix	–	155	39.54
Homoeothrix janthina	1310	4927	18.93
Hydrococcus	863	143	23.25
Hydrurus foetidus	1873	1210	23.90
Jaaginema	–	181	6.55
Klebsormidium	6474	32	7.55
Komvophoron	–	3	0.87
Leptolyngbya	189418	1106	9.81
Limnothrix redekei	–	22	2.23
Lyngbya	–	14	1.27
Merismopedia	727	96	9.23
Mougeotia	7055	44	0.72
Nostoc	1146	5	1.67
Oedogonium	8959	23	1.19
Oocystis	5827	8	2.67
Oscillatoria	917	51	5.44
Pediastrum	–	2	0.31
Phacus	9766	1	0.33

Table G3 (continued). Soft bodied algae taxa list and relative abundances from Stream Ecological Integrity monitoring at Glacier National Park, 2007–2009. Total counts are followed by mean relative abundances.

Taxa	Taxonomic Serial Number	Total count (2007–2009)	Mean relative abundance
Phormidium	992	895	5.78
Pleurocapsa	1435	12	3.58
Pseudanabaena	1175	190	2.45
Pseudophormidium	189422	21	5.56
Scenedesmus	6104	63	1.92
Schizothrix	667866	4	1.33
Selenastrum	6249	3	1.00
Spirogyra	6996	6	1.91
Staurastrum	7440	9	0.50
Stigeoclonium	6651	1617	9.51
Synechocystis	799	102	3.23
Tetrastrum	6260	8	2.38
Tolypothrix	1330	8	2.65
Trachelomonas	9690	2	0.63
Tribonema	2053	16	2.64
Ulothrix	6417	4	0.39
Ulothrix zonata	6431	118	7.44
Zygnema	7100	15	2.41
Empty diatom cells	–	1771	30.56
Unknown Bluegreen	–	3	0.54
Unknown chrysophyte	–	11	3.67
Unknown coccoid	–	33	1.17
Unknown coccoid	–	98	7.88
Unknown coccoid	–	3	0.94
Unknown flagellate	–	3	0.45
Total		**35617**	**6.74**

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