



Marine Water Quality in Pacific Island National Parks

Temporal, spatial, and chemical patterns 2008–2015

Natural Resource Report NPS/PACN/NRR—2021/2220





The production of this document cost \$278,839, including costs associated with data collection, processing, analysis, and subsequent authoring, editing, and publication.

ON THIS PAGE

Kalaupapa National Historical Park
NPS photo by Eric Brown

ON THE COVER

Ofu, National Park of American Samoa
NPS photo by Visa Vaivai

Marine Water Quality in Pacific Island National Parks

Temporal, spatial, and chemical patterns 2008–2015

Natural Resource Report NPS/PACN/NRR—2021/2220

David F. Raikow¹, Scott Kichman¹, Amanda L. McCutcheon¹, and Anne Farahi¹

¹National Park Service
I&M, Building 22
1 Crater Rim Dr.
Hawai‘i National Park, HI 96718

January 2021

U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

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.

The Natural Resource Report Series is used to disseminate comprehensive information and analysis about natural resources and related topics concerning lands managed by the National Park Service. The series supports the advancement of science, informed decision-making, and the achievement of the National Park Service mission. The series also provides a forum for presenting more lengthy results that may not be accepted by publications with page limitations.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner.

Data in this report were collected and analyzed using methods based on established, peer-reviewed protocols and were analyzed and interpreted within the guidelines of the protocols.

Views, statements, findings, conclusions, recommendations, and data in this report do not necessarily reflect views and policies of the National Park Service, U.S. Department of the Interior. Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the U.S. Government.

This report is available in digital format from [Pacific Island Network Inventory & Monitoring program website](#), and the [Natural Resource Publications Management website](#). If you have difficulty accessing information in this publication, particularly if using assistive technology, please email irma@nps.gov.

Please cite this publication as:

Raikow, D. F., S. Kichman, A. L. McCutcheon, and A. Farahi. 2021. Marine water quality in Pacific Island national parks: Temporal, spatial, and chemical patterns 2008–2015. Natural Resource Report NPS/PACN/NRR—2021/2220. National Park Service, Fort Collins, Colorado.
<https://doi.org/10.36967/nrr-2284328>.

Contents

	Page
Figures.....	v
Tables.....	vii
Appendices.....	vii
Executive Summary	viii
Acknowledgments.....	x
List of Acronyms	xi
Introduction.....	1
General Biochemistry.....	3
Land-Sea Interaction	4
Global-Scale Climate Phenomena.....	5
Ecological Context	6
Methods.....	7
Sample Sites	7
Sampling Regime	11
Water Collection.....	13
Dissolved and Particulate Nutrient Fractions	13
Weather and Tides.....	13
Physiochemical Parameters and General Conditions	13
Data Management and Quality Control.....	14
Spatial Analysis.....	14
Correlation of Surface and Bottom Samples	14
Comparison of Fixed and Temporary Sites.....	14
Estimation of Parameter Value Ranges.....	15
Correlation of terrestrial rainfall and salinity at Kaloko-Honokōhau NHP.....	15
Trend Analysis.....	15

Contents (continued)

	Page
Results.....	18
General Water Quality.....	18
Trends.....	21
Note Concerning National Park of American Samoa.....	21
Spatial Patterns.....	29
Dissolved and Particulate Nutrient Fractions.....	34
Seasonality.....	35
Surface and Near-bottom Sample Correlation.....	36
Comparison of Fixed and Temporary Sites.....	37
Climatological Context.....	38
Summary of results by park.....	42
War in the Pacific National Historical Park.....	43
National Park of American Samoa.....	43
Discussion.....	44
Submarine groundwater discharge and surface runoff.....	47
Climate and Temporal Patterns.....	50
Implications for Monitoring Protocol Design.....	54
Summary of Recommendations.....	56
Literature Cited.....	57

Figures

	Page
Figure 1. Park units of the Pacific Island Network, Inventory and Monitoring Division, National Park Service.	2
Figure 2. Marine water quality sample sites in Kaloko-Honokōhau National Historical Park 2008–2015.	8
Figure 3. Marine water quality sample sites in National Park of American Samoa at Tutuila (upper panel) and Ofu (lower panel) 2008–2015.	9
Figure 4. Marine water quality sample sites in Kalaupapa National Historical Park 2008–2015.....	10
Figure 5. Marine water quality sample sites in War in the Pacific National Historical Park 2008–2015.	12
Figure 6. Distribution of selected marine water quality parameters measured during typical conditions at the surface in PACN parks, 2008–2015.	19
Figure 7. Distribution of selected marine water quality parameters measured during typical conditions near the bottom in PACN parks, 2008–2015.....	20
Figure 8. Water quality parameters in marine waters of Kaloko-Honokōhau National Historical Park, 2009–2015.	23
Figure 9. Water quality parameters in marine waters of Kalaupapa National Historical Park, 2009–2015.	24
Figure 10. Water quality parameters in marine waters of War in the Pacific National Historical Park, Asan Marine Unit, 2009–2015.....	25
Figure 11. Water quality parameters in marine waters of War in the Pacific National Historical Park, Agat Marine Unit, 2009–2015.	26
Figure 12. Water quality parameters in marine waters of National Park of American Samoa, Island of Tutuila, 2009–2015.	27
Figure 13. Water quality parameters in surface marine waters of National Park of American Samoa, Island of Ofu, 2009–2015.....	28
Figure 14. Spatial distribution of surface total dissolved phosphorus in marine waters of Kaloko-Honokōhau National Historical Park illustrating multiple observations of increased nutrient concentrations near the Honokohau Harbor mouth.	30

Figures (continued)

	Page
Figure 15. Spatial distribution of surface salinity in marine waters of Kaloko-Honokōhau National Historical Park illustrating multiple observations of less saline water at the mouth of Honokohau Harbor.	31
Figure 16. Spatial distribution of bottom salinity in marine waters of Kaloko-Honokōhau National Historical Park illustrating spatially homogenous conditions in contrast to surface conditions.	32
Figure 17. Spatial distribution of surface turbidity in marine waters of Kaloko-Honokōhau National Historical Park illustrating a high-turbidity event in 2010 Q4.	33
Figure 18. Oceanic Niño Index (NOAA 2018) compared to rainfall at Kaloko-Honokōhau National Historical Park (using LOESS smoothing, FA667668 Kaloko Honokohau Hawaii).	38
Figure 19. Nearshore salinity compared to rainfall at Kaloko-Honokōhau National Historical Park (FA667668 Kaloko-Honokōhau Hawaii).	39
Figure 20. Oceanic Niño Index compared to total monthly rainfall at Kalaupapa National Historical Park.	40
Figure 21. Oceanic Niño Index compared to total monthly rainfall at War in the Pacific National Historical Park.	41
Figure 22. Oceanic Niño Index compared to total monthly rainfall at National Park of American Samoa.	41

Tables

	Page
Table 1. National parks monitored for marine water quality by the Pacific Island Network (PACN).	1
Table 2. Phosphorus (P) and Nitrogen (N) nutrient species found in aquatic ecosystems.....	3
Table 3. Trends detected in marine water quality parameters at PACN national parks.....	21
Table 4. Summary of the distribution of dissolved nutrient proportions (%) phosphorus (P) and nitrogen (N) in the marine waters of selected pacific island parks.	34
Table 5. Number of test statistical test permutations with significant seasonality results (maximum = 4) for all PACN parks.	35
Table 6. Correlation coefficients (R) for surface and bottom samples in marine areas of PACN parks.	36
Table 7. Summary of Mann-Whitney tests (p) comparing data collected at surface fixed and temporary sites.	37
Table 8. Correlation (r) of nearshore salinity and monthly average precipitation at Kaloko-Honokōhau National Historical Park (KAHO).	39
Table 9. Nutrient concentration means or ranges in groundwater, directly measured submarine groundwater discharge (SGD), SGD plumes, and/or ambient Pacific island nearshore seawater.	45

Appendices

	Page
Appendix A. R code.....	64
Appendix B. Tests for Seasonality.....	80
Appendix C. Results of Statistical Trend Tests	92
Appendix D. Ranges of water quality parameters	102
Appendix E. Data Censoring	105
Appendix F. Distribution of dissolved nutrient fractions	107
Appendix G. Comparison of Fixed and Temporary Sites.....	110

Executive Summary

Marine water quality was monitored along the coasts of Kaloko-Honokōhau National Historical Park on the Island of Hawai‘i, Kalaupapa National Historical Park on Moloka‘i, War in the Pacific National Historical Park on Guam, and National Park of American Samoa on Tutuila and Ofu, from 2008 to 2015. Concentrations of nitrogen and phosphorus were measured by collecting water samples. Temperature, dissolved oxygen, salinity, turbidity, chlorophyll, and pH were measured using probes. Analyses and summaries include the ranges of water quality parameter values under ordinary conditions, trends, spatial patterns, seasonal patterns, the abundance of nutrients in dissolved and particulate forms, correlation between surface and near-bottom water measurements, and a comparison of fixed and temporary sites.

Waters were low in total dissolved phosphorus (TDP), with concentrations generally at or below the 15.0 µg/L detection limit. Waters were low in total dissolved nitrogen (TDN) with concentrations centered close to the detection limit, of 0.07 mg/L with outliers up to 0.44 mg/L. Nitrate + nitrite ($\text{NO}_3^- + \text{NO}_2^-$) concentrations ranges were centered at or below ~10 µg/L. Near-bottom waters had lower concentrations of nutrients than surface waters. Fixed and temporary sites did not differ substantially with regard to any parameter. Waters were high in dissolved oxygen, low in turbidity, and thus oligotrophic and consistent with previous studies. Results did not merit concern with regard to water quality with two exceptions: 1) Honokohau Small Boat Harbor near Kaloko-Honokōhau National Historical Park consistently released a plume of water that was cold, fresh, and high in nutrients, e.g. $\text{NO}_3^- + \text{NO}_2^-$ up to 166 µg/L; and 2) a possible algal bloom was observed in Kaloko-Honokōhau National Historical Park in 2010 that did not appear to be caused by the harbor.

Very few temporal changes were observed over the study period. A ~25% decrease in TDN was observed at Kalaupapa National Historical Park from 2013 to 2014, which continued into 2015. Decreasing salinity of 1–2 parts-per-thousand (ppt) was detected over the study period (2008–2015) in Kaloko-Honokōhau National Historical Park, Kalaupapa National Historical Park, War in the Pacific National Historical Park Asan unit, and National Park of American Samoa Ofu unit. Increasing temperatures of up to 2°C were detected at Kaloko-Honokōhau National Historical Park and up to 1°C at Kalaupapa National Historical Park during the latter portion of the study period; but this may have been an artifact of relatively low values at the beginning, and high values at the end of the observation period. Nutrients existed almost completely in dissolved forms. Seasonality was suggested for temperature and chlorophyll. Spatial patterns were only detected at Kaloko-Honokōhau National Historical Park with respect to the previously-known plume emanating from Honokohau Small Boat Harbor. Surface and near-bottom measurements were highly correlated.

Temporal changes in salinity and temperature could be explained by the timing of weather affected by the El Niño Southern Oscillation. The monitoring period began with El Niño conditions, followed by a short La Nina, an extended neutral period, and ended with the beginning of another El Niño. At Kaloko-Honokōhau National Historical Park, very low rainfall in 2009 reduced available freshwater contributions to groundwater, likely resulting in less fresh water being released as submarine groundwater discharge, thus increasing local marine salinity. Later high rainfall increased available

freshwater contributions to groundwater resulting in decreased salinity. Temporal changes observed over the study period therefore likely did not indicate long-term change or immediate cause for management concern.

This study revealed aspects of methodology that could be improved in future monitoring efforts. The site selection method did not capture spatial heterogeneity present in near-shore habitats despite protocol objectives explicitly stating that spatial variance was to be measured. Addition of fixed sample sites optimized to capture spatial patterns, and removal of randomly selected temporary sites, is recommended. The timing of sampling did not account for tidal stage or recent rainfall events. Sampling during ebb tides and after river discharge event have subsided is recommended. Multiple depths were sampled at high monetary cost with limited scientific insight. Surface and selected true bottom sampling are recommended as surface and near-bottom samples were similar and correlated, near-bottom samples failed to capture conditions at the bottom, and near-bottom samples revealed no temporal patterns not observed at the surface. Recommended improvements will reduce monetary cost, reduce field time, improve understanding, and maintain long-term monitoring data sets.

Acknowledgments

For their contributions to implementing and improving the PACN water quality protocol we thank Gary Rosenlieb, Pete Penoyer, Joe DeVivo, John Marra, Joshua Walston, Sallie Beavers, Sean Eagan, Eric Brown, Mike Gawel, Justin Mills, Visa Vaivai, Sylvester Lee, Sheila McKenna, Rebecca Weissinger, Greg Kudray, Ryan Monello, Tara Holitzki, Erik Johnson, Eric Dinger, and an anonymous reviewer.

List of Acronyms

C	Carbon
CO ₂	Carbon Dioxide
DOP	Dissolved Organic Phosphorus
ENSO	El Niño Southern Oscillation
EPA	Environmental Protection Agency
FNU	Formazin Turbidity Units
IDW	Inverse Distance Weighting
IMD	Inventory and Monitoring Division
IPO	Interdecadal Pacific Oscillation
KAHO	Kaloko-Honokōhau National Historical Park
KALA	Kalaupapa National Historical Park
N	Nitrogen
NH ₄ ⁺	Ammonium
NHP	National Historical Park
NO ₂ ⁻	Nitrite
NO ₃ ⁻	Nitrate
NOAA	National Oceanic and Atmospheric Administration
NPS	National Park Service
NPSA	National Park of American Samoa
NRDS	Natural Resource Data Series
NRR	Natural Resource Report
NTU	Nephelometric Turbidity Units
ODO	Optical Dissolved Oxygen
P	Phosphorus
PP	Particulate Phosphorus
PPT	Parts-per-thousand
PACN	Pacific Island Network
Q1–4	Calendar year quarters 1 through 4
RAWS	Remote Automatic Weather Station
SCUBA	Self Contained Underwater Breathing Apparatus
SGD	Submarine Groundwater Discharge
SpC	Specific Conductivity
SPCZ	Southern Pacific Convergence Zone
SRP	Soluble Reactive Phosphorus (Phosphate)
TDN	Total Dissolved Nitrogen
TDP	Total Dissolved Phosphorus
TN	Total Nitrogen
TP	Total Phosphorus
U.S.C.	United States Code
USGS	United States Geological Survey
WAPA	War in the Pacific National Historical Park

Introduction

Water quality is widely used as an indicator of marine-ecosystem condition (Kardis and Kitsiou 2013). Accordingly, the National Park Service (NPS) designated water quality as a “vital sign,” or an indicator of physical, chemical, biological elements or ecosystem processes that represents the overall health and condition of natural resources within parks (HaySmith et al. 2005). Due to potential stressors such as nutrient enrichment, invasive species, recreational use, and presence of sensitive ecosystems such as coral reefs, water quality is a vital sign monitored by the NPS Inventory and Monitoring Division (IMD), Pacific Island Network (PACN, Figure 1). The primary objectives of this program include determining the range, spatial patterns, and temporal trends of water quality parameters in the coastal marine waters of four parks (Jones et al. 2011; Table 1). Secondary objectives included determining particulate and dissolved nutrient fractions, and correlation of parameters in surface and near-bottom samples.

Table 1. National parks monitored for marine water quality by the Pacific Island Network (PACN).

Park	Island	State or Territory
Kaloko-Honokōhau National Historical Park (KAHO)	Hawai'i	Hawaii
Kalaupapa National Historical Park (KALA)	Moloka'i	Hawaii
War in the Pacific National Historical Park (WAPA)	Guam	Guam
National Park of American Samoa (NPSA)	Tutuila, Ofu	American Samoa

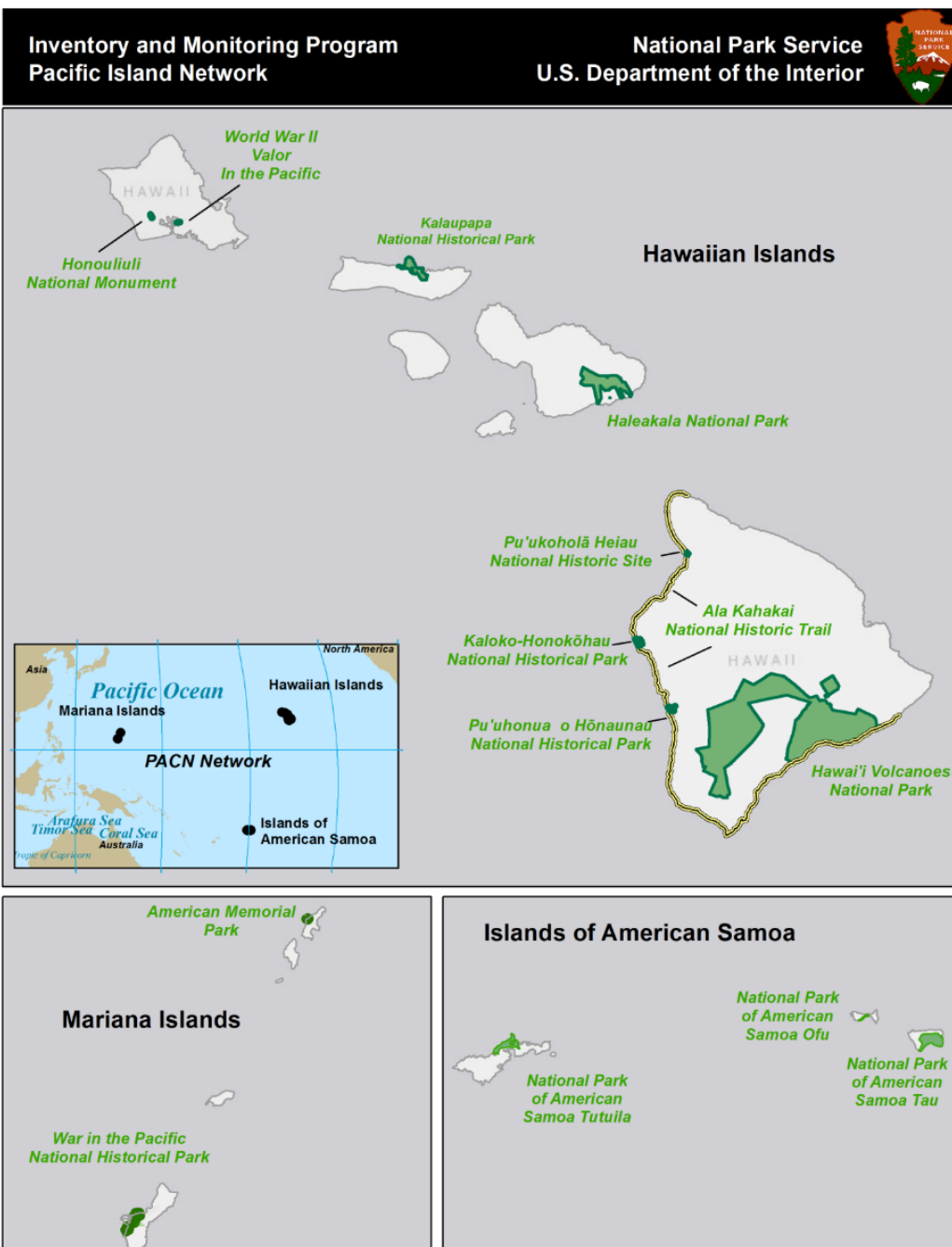


Figure 1. Park units of the Pacific Island Network, Inventory and Monitoring Division, National Park Service.

This Natural Resource Report (NRR) presents comprehensive information and analysis about natural resources in lands managed by the NPS for the purpose of informing park managers on current conditions and temporal trends in ecosystem health. Additional information on water quality in the marine portions of PACN parks can be found in Natural Resource Data Series reports (NRDS, Raikow, Farahi, Kichman, and McCutcheon 2017; Raikow, Farahi, McCutcheon et al. 2017; Raikow,

Farahi, McCutcheon, Fuiava et al. 2017; Raikow, Farahi, McCutcheon, and Kichman 2017). Park managers can use this information to evaluate resource conditions and potential impacts and mitigation measures for their park and watersheds.

General Biochemistry

One focus of PACN water quality monitoring is determining nutrient concentrations, particularly nitrogen (N) and phosphorus (P), because of their potential to alter algae communities and cause blooms. All organisms require N and P, which exist in several forms called “nutrient species” (Table 2). Characteristics of nutrient species important to water quality include being dissolved or particulate, being contained within or derived from organisms (organic) or inorganic, and being easily used by organisms (labile) or recalcitrant. All dissolved and particulate nutrient species are either organic or inorganic, and vary with regard to how easily they are used by organisms. Total phosphorus (TP) and total nitrogen (TN) are measures of all the P and N in a sample. To measure the dissolved fraction of nutrients, water must be filtered to remove particles including microorganisms. In addition to nutrients there are physical and chemical characteristics commonly included in evaluations of water quality in any aquatic ecosystem, such as oxygen content, pH, turbidity, temperature, and salinity.

Table 2. Phosphorus (P) and Nitrogen (N) nutrient species found in aquatic ecosystems.

Nutrient Species	Symbol	Components
Total Phosphorus	TP	PP + TDP
Particulate Phosphorus	PP	Algae, zooplankton, detritus, P in or on inorganic particles
Total Dissolved Phosphorus	TDP	SRP + DOP
Soluble Reactive Phosphorus	SRP	PO ₄ , phosphate, orthophosphate, or inorganic phosphorus
Dissolved Organic Phosphorus	DOP	P in organic molecules derived from organisms
Total Nitrogen	TN	PN + TDN
Particulate Nitrogen	PN	Algae, zooplankton, detritus, N in or on inorganic particles
Total Dissolved Nitrogen	TDN	DIN + DON
Dissolved Inorganic Nitrogen	DIN	NH ₄ ⁺ + NO ₃ ⁻ + NO ₂ ⁻
Dissolved Organic Nitrogen	DON	N in organic molecules derived from organisms
Ammonium	NH ₄ ⁺	Sometimes reported as ammonia N
Nitrate	NO ₃ ⁻	Often reported as NO ₃ ⁻ + NO ₂ ⁻
Nitrite	NO ₂ ⁻	Often reported as NO ₃ ⁻ + NO ₂ ⁻

Both the N and P cycles have been altered at the global scale by human influence (reviewed by Vitousek et al. 1997; Smil 2000). Fertilizer production and use, fossil fuel combustion, growing N₂-fixing crops, spreading N₂-fixing invasive plants, and mobilizing nutrients through processes such as surface water runoff has increased the amount of N and P readily available to all organisms. At the local scale, agricultural runoff and sewage effluent deliver large nutrient loads to coasts. Such alteration of nutrient cycles is a primary motivation for monitoring nutrient concentrations in aquatic ecosystems, as is the release of organisms from previous nutrient availability limitation, the effect of carbon-nitrogen-phosphorus (C:N:P) ratios and relative abundances of nutrient species on food-web structure and the planktonic community, and the toxicity of some nutrient species to aquatic animals at high concentrations (Camargo and Alonso 2006; Sardans et al. 2012; Gilbert 2012).

Other constituents of water are governed by large scale processes. For example, seawater developed a pH of 8.1 over geologic time and global spatial scales (Lau and Mink 2006). However, since atmospheric carbon dioxide (CO₂) exists in equilibrium with dissolved CO₂ by forming carbonic acid in water, increased global atmospheric CO₂ increases carbonic acid concentrations and lowers pH (ocean acidification). In contrast, at local scales consumption of CO₂ by autotrophs through photosynthesis reduces carbonic acid and raises pH. Marine surface waters generally have low turbidity (cloudiness), except when wave action suspends sediments, when sediments are delivered to coastal areas by terrestrial runoff, and during algal blooms. Temperature and salinity in near-shore marine waters can vary seasonally and regionally. Hawaiian coastal waters have been described as moderately warm and saline ($\sim 25^{\circ}\text{C} \pm 1^{\circ}\text{C}$ and $\sim 35\text{‰} \pm 0.2\text{‰}$ respectively; Lau and Mink 2006).

Land-Sea Interaction

Marine water quality is monitored here in near-shore waters, so it is important to consider physical conditions that could affect water quality parameters in these habitats. Beginning at the seabed, nutrients and other materials derived from the seabed itself are mixed into the overlying water column in the near-shore environments of Pacific islands within 0.5 to 1m above the sea floor (C. Storlazzi, USGS, personal communication). Mixing is driven by wave-action, itself driven by winds (Thorpe 2007). All marine waters in PACN parks are within a surficial mixed oceanic layer, when the entire ocean water column is considered. In contrast, open marine waters far from shore are stratified into a surface layer mixed by wind and extending up to 100m deep over colder and more nutrient-enriched water (Lau and Mink 2006). The biogeochemistry of oceanic island nearshore environments is influenced by the interaction between terrestrial meteoric precipitation, porous landforms, and surface runoff to coastlines. Nearshore marine water can thus include a 1–2 m thick layer of water at the surface that is often cooler and less saline than deeper water as a result of inputs of land-derived waters (Garrison et al. 2003; Johnson et al. 2008).

Windward coasts of Pacific islands typically have high annual rainfalls, high rates of aquifer recharge, high erosion rates, and well-developed stream networks (Lau and Mink 2006). Terrestrial runoff to coastlines is known to supply nutrients that negatively impact corals and promote macroalgae, particulate organic matter consumable by corals and other filter feeders, and sediment that reduces light penetration and directly disturbs corals (Fabricius 2005; Wiegner et al. 2017). Leeward sides of islands receive less precipitation and the establishment of surface drainage channels

can be prevented when precipitation penetrates the surface (Oki 1999, Moore 1999). Rain becomes fresh groundwater and mixes with seawater infiltrating terrestrial aquifers creating brackish groundwater lenses (Moore 1999). Underling geological features such as lava tubes can transmit water quickly, while lava dykes can impede groundwater flow, resulting in perched aquifers (Oki 1999; Taboroši et al. 2004; Knee and Paytan 2011).

Importantly, brackish water is expelled into the marine nearshore environment as submarine groundwater discharge (SGD, reviewed by Taniguchi et al. 2002, Burnett et al. 2003). Submarine groundwater discharge is an example of ecological subsidy, whereby nutrients and energy are derived from one area or ecosystem, and then supplied to another ecosystem and used by organisms (Polis and Power 2004). Ecosystems frequently exchange resources mutually, but typically through different mechanisms. In contrast, shorelines discharging groundwater can experience a unique, continual, rapid, and reciprocal exchange mediated by tides moving water between open offshore water and the subterranean terrestrial aquifer (Li et al. 1999, Moore 1999, Robinson et al. 2007). Pulses of SGD to the nearshore marine environment can occur immediately after terrestrial rainfall events (Taniguchi 2002). Other factors driving SGD include geothermal heating inducing large-scale circulation patterns of groundwater through shoreline aquifers, which may have significance on the Island of Hawai‘i due to the presence of active volcanoes, wave action, seabed topography, and sediment porosity (Moore 1999; Taniguchi et al. 2002; Burnett et al. 2003).

Global-Scale Climate Phenomena

The El Niño Southern Oscillation (ENSO, Wang et al. 2016) cycle may affect nearshore park environments. During neutral conditions, westerly trade winds push warm surface water to the western Pacific while cool water upwells in the east. This temperature differential creates the Walker circulation, or warm, moisture-laden air rising in the west and cool, dry air sinking in the east. During the cooling “La Niña” phase trade, westerly winds increase causing cool eastern water to extend across the Pacific intensifying the temperature differential, increasing rain in the western Pacific. During the warming “El Niño” phase, westerly winds weaken allowing warm surface water to extend east across the Pacific, disrupting the Walker circulation and increasing rain in the eastern and central Pacific and decreasing rain in the west. General island effects vary by location (Sutton et al. 2016). ENSO effects occur in the western pacific first and move eastward over time (Rupic et al. 2018). Rainfall increases and sea surface temperatures fall during developing and mature El Niños, then rain decreases, and sea surface temperatures rise (Rupic et al. 2018). Factors such as SGD and ENSO may affect water quality patterns necessitating careful interpretation of long-term monitoring data.

Ecological Context

The relevance of monitoring data to ecosystems is limited to its ecological context, or “inference space” (Mueller et al. 2015). Note that the “sampling frame,” or source material from which samples are taken, is not the same as the ecological context. Here the sampling frame is all safely accessible marine waters within park boundaries (Jones et al. 2011). Recognizing the ecological context to which monitoring data applies prevents overextending interpretation into conclusions not supported by data. The ecological context for data collected here is defined by several dimensions:

- **Distance from shore.** The prevalence of SGD in Pacific islands, especially those of recent volcanic origin, requires considering whether sample sites might occur close enough to shore to directly sample, or be affected by, SGD plumes and surface water discharge.
- **Depth.** SGD plumes are often found near the sea surface, and therefore surface samples might differ from samples taken at lower depths regardless of long-term trends.
- **Location along the shoreline.** Landscape features such as fishponds, harbors, river mouths, and SGD plume sources must be considered due to potential influences on local conditions.
- **Time.** Consideration of when samples are taken is important. Ebb tides (moving offshore) draw out SGD and flood tides (moving inland) push seawater into coastal aquifers. Annual seasonality may occur in some parameters. Climatic phenomena occurring over multiple years must also be considered as potential drivers of temporal patterns.
- **Intermittent events.** The estimation “ordinary” or baseline parameter value ranges and long-term trends must exclude storms, algal blooms, and surface runoff discharge events. Though natural, such occurrences are short-term deviations from otherwise ambient conditions, and thus confound evaluation of long-term trends. Estimation of ranges for ordinary conditions establishes objective criteria for identifying and quantifying intermittent and atypical events, including those of concern to natural resource managers.

Methods

Water was collected for nutrient analyses, a sonde equipped with multiple probes was used to measure water quality parameters, and weather conditions were recorded. Data were collected from 2008–2015 using methods described in version 1.0 of the PACN water quality protocol (Jones et al. 2011; described below). The sampling regime was based on a split-panel of permanently established or “fixed” sites sampled during each sampling effort, and “temporary” sites with randomly assigned locations, for each sampling effort.

Sample Sites

Kaloko-Honokōhau National Historical Park (NHP) is located on the leeward side of the Island of Hawai‘i along the western, or Kona, coast, and encompasses a 2.5 km² marine area (Figure 2). The Island of Hawai‘i is the geologically youngest of PACN sample sites at up to 0.6 million years old and has portions still in the shield-building volcanic stage of development characterized by active lava flows (Ziegler 2002). The Kona coast is young and hydrologically dynamic, having been formed by lava flows as recent as 1801 A.D. from the upslope active volcano Hualālai (Oki 1999; Lau and Mink 2006). The park consists of one continuous unit that includes about 600 acres of submerged marine land and the adjacent coastal area. Globally rare, brackish, tidally influenced coastal anchialine pools are numerous in Kaloko-Honokōhau NHP. Two large brackish fishponds (‘Aimakapā and Kaloko) are also located within the park, and the Honokohau Small Boat Harbor is adjacent to the park to the south. No overland surface flow of water occurs in the park, and SGD is an important phenomenon occurring in the near-shore marine environment.

National Park of American Samoa consists of units on three islands with two marine portions totaling 12.9 km² (Figure 2). The 1.4 million year-old archipelago is a series of eroded volcanic remnants, dominated by the Island of Tutuila in American Samoa (Birkeland 2007). The primary marine portion of the park is located along the northern windward shore of Tutuila and receives high precipitation with discharge from several streams. The marine section of the Ofu unit of National Park of American Samoa is located on the leeward side of the Island of Ofu. Kalaupapa NHP includes a 7.8 km² marine area, is located on the windward northern shore of the Island of Moloka‘i (Figure 3), and has a mix of volcanic origins. Extremely tall sea cliffs ~2 million years old are derived from the erosional volcanic stage (Zielger 2002). The northern Moloka‘i coastline receives very high precipitation through rainfall, in contrast to Kaloko-Honokōhau NHP. Deep valleys drained by streams discharge freshwater to nearshore environments, most prominently Waikolu Stream. Kalaupapa also encompasses a porous peninsula derived from 0.5 million year-old lava produced during a rejuvenation volcanic stage. War in the Pacific NHP is located on the Island of Guam (Figure 4). Although carbonate in origin, the 30 million year-old island has two distinct geologic regions. The northern portion of the island is an uplifted karst plateau of coral deposits, while the southern portion is uplifted weathered volcanic and carbonate deposits (Taboroši et al. 2004). Marine portions of War in the Pacific NHP, totaling 4.0 km², occur in the southern region of the island and are divided into the Asan Beach Unit to the north and Agat Unit to the south. The Asan River drains a small valley into the Asan marine park unit. Surface runoff is significant at both Asan and Agat (Storlazzi et al. 2009, 2014).



Figure 2. Marine water quality sample sites in Kaloko-Honokōhau National Historical Park 2008–2015.

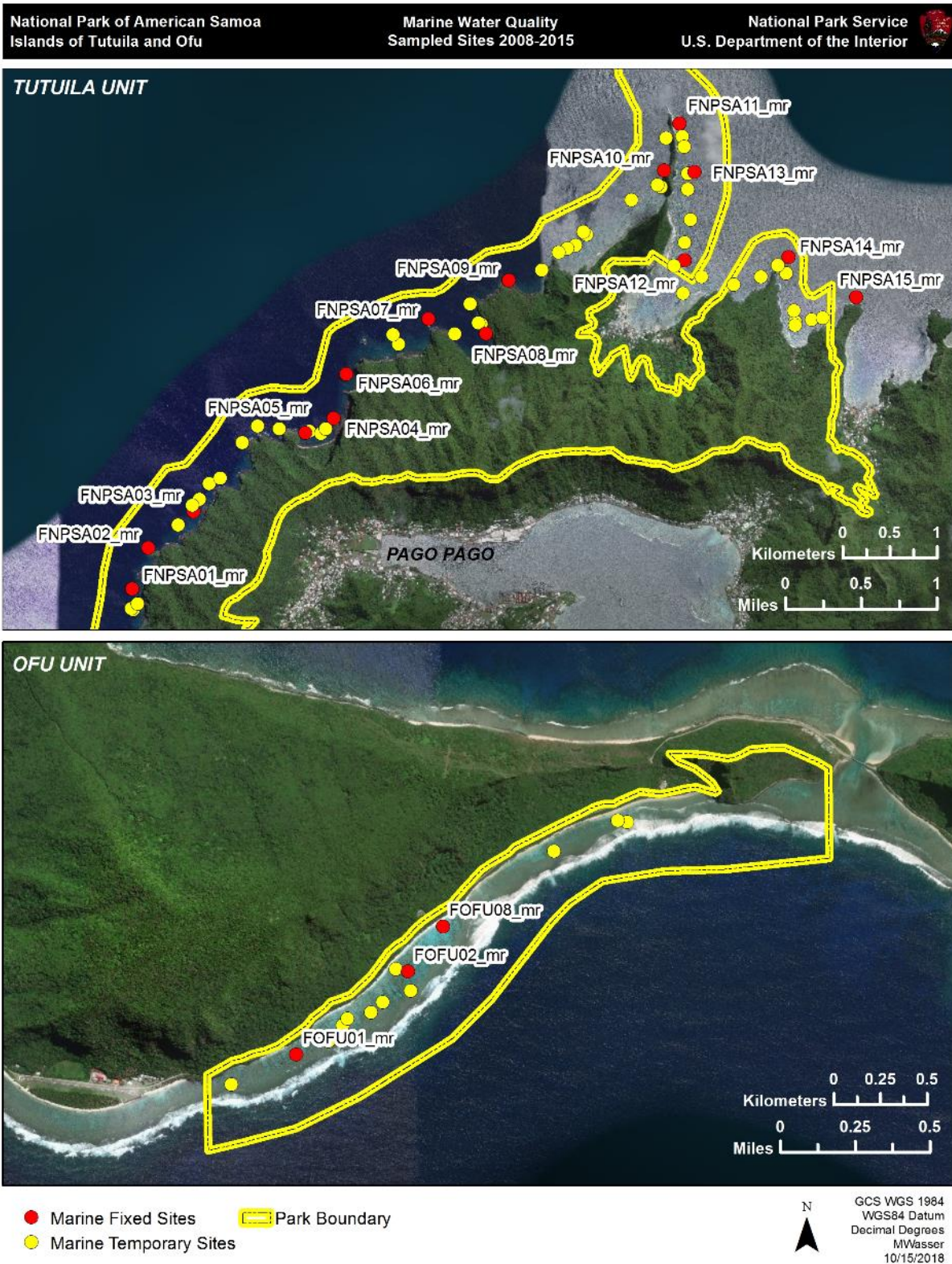


Figure 3. Marine water quality sample sites in National Park of American Samoa at Tutuila (upper panel) and Ofu (lower panel) 2008–2015.

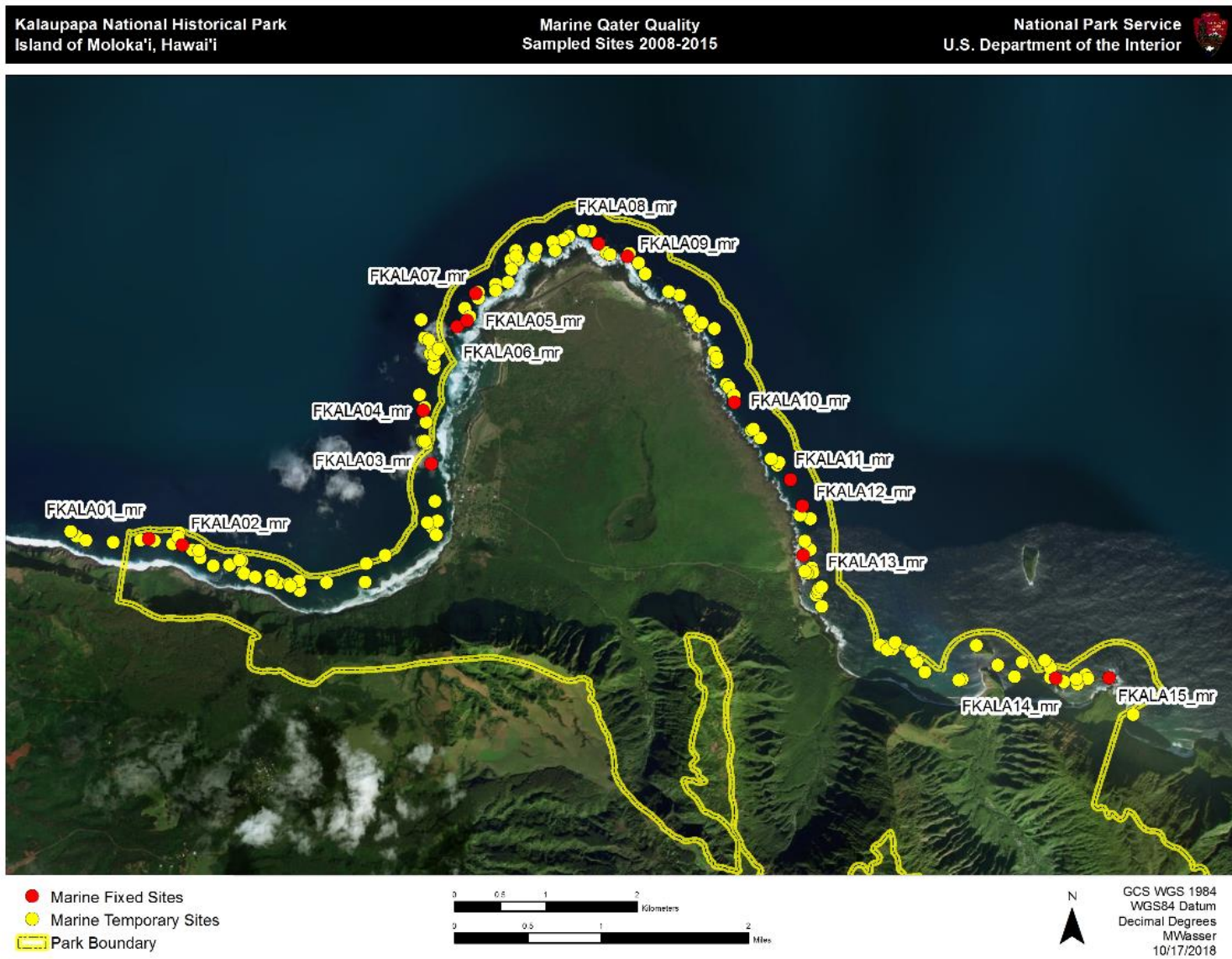


Figure 4. Marine water quality sample sites in Kalaupapa National Historical Park 2008–2015.

Sampling Regime

Site names used by PACN were formatted to designate fixed (F) or temporary sites (T), park (e.g. KAHO), a number (e.g. 01), and habitat type (“mr” for marine); e.g. “FKAHO01_mr”. Names for temporary sites were based on the date of sampling, e.g. “TKAHO01_20081014_mr”. Marine portions of parks were sampled from 2008 to 2015 with varying quarterly coverage. At Kaloko-Honokōhau NHP (Figure 2), the Tutuila area of National Park of American Samoa (Figure 3), and Kalaupapa NHP (Figure 4) we measured four fixed sites (fixed-site panel) and four temporary sites (temporary-site panel) generated at random during each sampling effort. In the Ofu unit of NPSA, four fixed sites were sampled in the lagoon area only (Figure 3). Two fixed sites and two temporary sites were sampled in each of the Agat and Asan units of War in the Pacific NHP (Figure 5). Surface and near-bottom water quality data were taken at all parks, except at Ofu where only surface samples were taken due to the area being shallow.

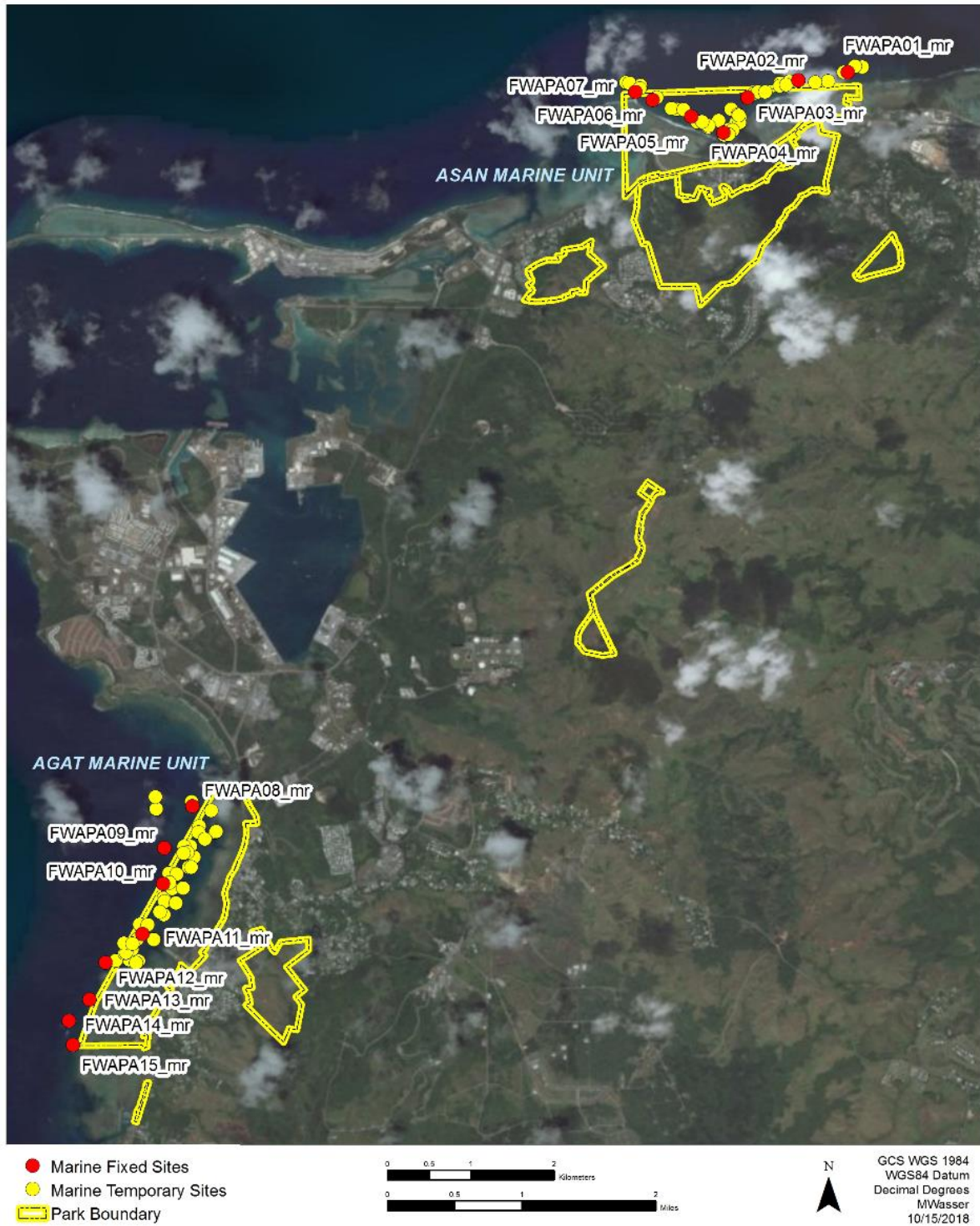


Figure 5. Marine water quality sample sites in War in the Pacific National Historical Park 2008–2015.

Water Collection

A Niskin bottle was used to sample water within 1 m of the surface and at 2–3 m above the bottom, labeled “near-bottom” in the database. Water was dispensed from the Niskin bottle directly into an acid-washed syringe (2013–2015) or acid-washed filter tower (2013–2015) and filtered with 0.47 μm GF/F filters. Each bottle was rinsed three times with filtered site-water. A water sample was then filtered into each bottle. Three independent-grab 125 ml samples were taken at each, placed in a cooler with ice in the field, transferred to a freezer on the day of collection, and kept frozen until delivery to the EPSCoR University of Hawai‘i at Hilo (UHH) Analytical Laboratory at the Marine Science Department, for analysis. Analytes and their minimum detection limits included TDP (15.0 micrograms per liter or $\mu\text{g/L}$), TDN (0.070 milligrams per liter or mg/L), and $\text{NO}_3^- + \text{NO}_2^-$ (1.0 $\mu\text{g/L}$).

Dissolved and Particulate Nutrient Fractions

A study of the abundance of particulate and dissolved nutrient fractions was conducted because, although filtered samples had been collected since the start of the monitoring program, the protocol had not clearly specified sampling of total or total dissolved nutrients. This study was conducted at Kaloko-Honokōhau NHP, Kalaupapa NHP, and War in the Pacific NHP. Both filtered and unfiltered samples were collected from 2013 to 2015. Nutrient fractions were deduced by subtracting total dissolved nutrient concentrations measured in filtered samples from total nutrient concentrations measured in unfiltered samples. Normally distributed variance in results can be expected by instrumentation and causes results to contain calculated proportions of dissolved nutrients greater than 100%, which is physically impossible, when dissolved fractions are very close to 100%.

Weather and Tides

Precipitation data was obtained from the Remote Automatic Weather Stations (RAWS) 915226 Guam International Airport, FA667668 Kaloko Honokohau Hawaii (maintained by NPS), FA9024CE Makapulapai Hawaii (maintained by NPS), and 920694 Pago Pago Airport WSO Airport. Tidal stage was recorded for each sample station, and different sites were sampled at different tide stages to some extent due to the length of time required to complete a sampling event.

Physiochemical Parameters and General Conditions

A multi-parameter sonde (YSI 6600) was calibrated within a few days before commencing field sampling. The sonde was used to measure depth (m), temperature ($^{\circ}\text{C}$), specific conductivity (SpC) in milli-Siemens per centimeter (mS/cm), pH, optical dissolved oxygen concentration (ODO) in mg/L , chlorophyll in $\mu\text{g/L}$, and turbidity in nephelometric turbidity units (NTU), which is equivalent to FNU turbidity units (USGS, unpublished). The sonde also reported salinity in parts-per-thousand (ppt) calculated from SpC, and dissolved oxygen in percent saturation (% ODOsat) calculated from ODO and temperature. Salinity and ODOsat are reported here. At each site, the sonde recorded readings every 30 seconds, was lowered to a depth of 1 m, allowed to log readings for at least five minutes, and then lowered to 2 to 3 m above the bottom and allowed to log readings for at least five minutes. Between sites the sonde was stored with probes immersed in freshwater. The mean and variance of stable values, isolated by depth, are reported. Global positioning system coordinates were recorded, and pictures taken.

Data Management and Quality Control

All data were entered into PACN databases. Data were downloaded from the YSI 650 control unit and readings from surface and bottom depths were identified and uploaded to databases. Accuracy of data entry into databases was verified by comparing database entries to the original datasheets by a person who did not enter the data into databases. Data were then certified by the PACN aquatic ecologist. Data were explored visually for certification by plotting time-series. Outlying data and data that deviated from regular temporal patterns were investigated. Corroboration between related parameters and field notes was used to identify possible causes of deviation from expected temporal patterns. Data determined to be unreliable due to instrument or sampling errors were flagged in databases and not included in analyses. Duplicate samples and spiked samples were used to monitor quality of measurements in laboratory nutrient analyses.

Spatial Analysis

Spatial distributions of water quality parameters were mapped for past data reports (2008–2014) and have been presented in Raikow, Farahi, Kichman, and McCutcheon 2017; Raikow, Farahi, McCutcheon et al. 2017; Raikow, Farahi, McCutcheon, Fuiava et al. 2017; and Raikow, Farahi, McCutcheon, and Kichman 2017. Data were plotted spatially in ArcMap 10.3.1 (ESRI, Redlands, CA). The spatial distribution of parameter values at the surface across the marine portion of the park was plotted using the Inverse Distance Weighting (IDW) spatial analyst tool, which is based on the principle that values close to one another are more alike than those that are farther apart. We used a variable search radius with 12 points. Such settings, along with the number and dispersion of sample points, affect the appearance of interpolations. Sample locations were not originally chosen to optimize spatial analysis, and sample sites fell generally on a transect line running parallel to the shoreline (see Figure 3). Thus, interpolation along the axis perpendicular to the shoreline was less reliable. Based on this, a power option of seven was chosen, which decreased the significance of surrounding points and produced a visual banding effect. Interpolation was also limited to an area within 250 m of all sample points, to avoid displaying results in areas where no samples were taken.

Correlation of Surface and Bottom Samples

The degree to which samples and measurements taken at the surface were correlated with samples and measurements taken at deeper depths was evaluated with Pearson correlation to evaluate similarity in patterns between depths and thus the necessity of sampling at lower depths. Data were means of all sites sampled during a quarter. Correlation coefficients range from -1.0 to 1.0 . Positive values indicate a positive correlation and negative values indicate a negative correlation. The larger the absolute value of the coefficient the stronger the correlation (e.g., a 1.0 score would indicate that surface and bottom samples were perfectly and positively correlated).

Comparison of Fixed and Temporary Sites

Fixed sites and temporary sites were compared using the non-parametric Mann Whitney test. Data were values collected at all surface fixed sites within a sampling effort and all surface temporary sites within a sampling effort. At Kaloko-Honokōhau National Historical Park sites under the influence of the Honokohau Small Boat Harbor were analyzed separately from other sites.

Estimation of Parameter Value Ranges

The ranges of water quality parameter values were estimated for each park by summarizing the distribution of data collected during the entire study period. Data from National Park of American Samoa was subdivided into Tutuila and Ofu units, and data from War in the Pacific NHP was subdivided into Asan and Agat marine units. Data from Kaloko-Honokōhau NHP were subdivided into sites north of the Honokohau Small Boat Harbor plume, defined as all sites north of site FKAHO11_mr (Figure 2), and sites under the influence of the Honokohau Small Boat Harbor plume, defined as site FKAHO11_mr and sites south. All data for each park and unit was displayed as boxplots, and those data identified as outliers examined. Boxes represent the interquartile range, where the solid line represents the median, whiskers represent 1.5 times the interquartile range, and any data outside that range are represented as dots.

Correlation of terrestrial rainfall and salinity at Kaloko-Honokōhau NHP

An additional analysis was performed after initial data analyses to evaluate whether a consistent lag time existed between terrestrial rainfall and the delivery of meteoric freshwater to the shore at Kaloko-Honokōhau NHP. This analysis was conducted for Kaloko-Honokōhau NHP because of the well-documented high-volume SGD delivered to the near-shore marine environment. The correlation between salinity in the nearshore environment and monthly rainfall occurring in the past was evaluated. Pearson correlation was used to evaluate the relationship between salinity measured in a given month and total monthly precipitation of the same (current) month, the previous month, two, three, and four months back, and assorted averages, for both surface and bottom salinity measurements.

Trend Analysis

Choice of statistical methods for trend analysis was influenced by the nature of these data. The primary factors affecting choice of statistical tests were data censoring, seasonality, and sampling design. Data censoring is a limitation of measurement preventing values from being known, such as a detection limit. No trend analysis was conducted for instances where more than 50% of the data were censored (after Weissinger and Sharrow 2018). The non-parametric Mann-Kendall Tau was used to assess trend in nutrients, chlorophyll, and turbidity when 50% or less of the data were censored. The seasonal Mann-Kendall test was applied to censored parameters displaying seasonality. Trends in non-censored parameters were analyzed by linear mixed model (VanLeeuwen et al. 1996). Data analysis was completed using R v.3.5.0 (R Core Team 2017, see Appendix A). Mann-Kendall tests were evaluated using the EnvStats package for R (Millard 2013). Mixed models were evaluated with the lmer function.

Measurements from a series of water samples or sonde readings taken at an individual site within minutes of each other were assumed to be normally distributed around the true value of the parameter, as the parameter should not change appreciably over the short time required to take multiple samples or readings (but see censoring below). Variation in sample values should be most influenced by external factors. The water quality parameters at Ofu lagoon and the Tutuila marine area were analyzed separately. At Ofu lagoon where the water is shallow, nutrient samples were only

collected at the surface. For this reason, depth was not included as a factor in the mixed model trend analyses for Ofu, and bottom and surface samples were not compared for correlation analysis.

Data censoring occurs when there is a limit to the values a parameter may display or be detected. Here nutrients, chlorophyll, and turbidity had the potential to be censored. Non-detection of a nutrient analyte meant the value is less than the instrumental detection limit, but did not necessarily mean there was none present, even though that could have been the case. Any distribution of values can also be censored; for example, an otherwise normal distribution where one tail is truncated by the detection limit. Censored data are therefore non-parametric by definition and were analyzed with non-parametric methods (Helsel and Hirsch 2002, see below). Data censoring was evaluated for nutrients, turbidity, and chlorophyll. The value of the detection limit was used for censored replicates in the calculation of mean parameter values, by site.

The non-parametric, rank-based Mann-Kendall Tau scores parameter values as higher or lower than a median, without assessing the magnitude of departure. Kendall tests are robust when outliers, missing data, or censoring are present (Helsel and Hirsch 2002). Kendall tests were not adjusted for the possibility of serial correlation because datasets were less than 10 years in length. The seasonal Kendall test compares values within user-defined time-intervals such as months or quarters. Results are calculated for each time-interval and aggregated site (Helsel and Hirsch 2002). Thus, samples taken in the first annual quarter are compared only to other first-quarter samples. Trends within time intervals are combined to evaluate overall trend.

Seasonality was assessed for parameters prior to performing linear mixed model tests to determine if seasonal factors should be included in the model (Appendix B). Seasonality was evaluated using the multiple linear regression model function “lm” in R. Data were averaged to summarize the area and quarter. Wet and dry seasons were defined November through April (wet season for Hawaii and American Samoa, dry season for Guam) and May through October (dry season for Hawaii and American Samoa, wet season for Guam). Two models were considered: change over time and the effect of calendar-year quarters (q1, q2, q3), and change over time and the effect of the wet and dry seasons. These models were applied to two datasets: mean values calculated by lumping surface and near-bottom data at a site, and mean values of surface data only, with the exception of the Ofu unit at NPSA. In total, four tests for seasonality were performed for each location (all depths wet/dry seasons, all depths quarters, surface only wet/dry seasons, and surface only quarters), except at Ofu, where only the two surface data tests were performed. It is necessary to exclude a time-interval, e.g. “q4” and “dry”, in tests as these serve as references for the model. Season was included in the models of only a handful of trend tests. Thus, four tests for seasonality were performed for each parameter. Season was included in models only when strong evidence of seasonality was suggested, which was chosen to be having three significant tests.

The linear mixed model allowed for effects to be divided into fixed factors that impact the mean structure (e.g. depth, season, or quarter) and random factors that impact the variance structure (site and year). Variance was estimated by restricted maximum likelihood (REML), which is appropriate for unbalanced data such as split-panel design (Piepho and Ogutu 2002). Error for the random factors were partitioned into different sources of variation (site-to-site, year-to-year, and site-level estimates)

(Starcevich 2013). The model was run using the lmer function in the lmerTest package (Kuznetsova et al. 2016) in R (v3.4.0, R Core Team 2017) using R Studio (v1.0.143). The model (Appendix D), included fixed factors for time (WYEAR), depth, and seasonal factors when deemed appropriate by the seasonality analysis (Quarter or Season). The effect of site differences and random year-to-year variation were accounted for by including Station_ID and Year as random factors in the model.

Output of the lmer function included effect estimates and t-statistics for each fixed factor in the model and for the interaction between the time component WYEAR and depth. Full output of the linear mixed model displays the slope of the effect of the factor and the standard error for that value. Full output also displays the intercept estimate and its statistical significance, indicating if the slope of the factor is significantly different from zero. An interaction term “Time: Depth” was included in models. Such factors were included in models to account for the effect of these factors, and obtain model estimates better than a simple linear model, but individually these factors are not ecologically important and are not presented. The factor “Depth” tests for a difference between surface and bottom measurements. Additionally, *p*-values are estimated using Satterthwaite’s approximations (Kuznetsova et al. 2016). Effect estimates are not given for random factors, which are considered unobserved variables (Bates 2010; Bates et al. 2014).

Results

General Water Quality

Waters measured in the near shore environments of all parks were oligotrophic, or having low nutrient concentrations, high oxygenation, and low turbidity. Ranges of water quality parameters observed are summarized in Figures 6 and 7 and in Appendix D.

Total Dissolved Phosphorus. TDP was not detected or was observed at concentrations close to the detection limit of 15 µg/L at all parks. The detection limit for TDP in the present study was greater than TDP and SRP concentrations measured at a variety of Pacific islands by other studies, which used a variety of instruments and methods (see Discussion).

Total Dissolved Nitrogen. TDN concentration ranges were centered close to the detection limit of 0.07 mg/L with outliers up to 0.44 mg/L that varied to a lesser degree near the bottom than at the surface, with the exception of sites near Honokohau Small Boat Harbor at Kaloko-Honokōhau NHP having higher concentrations at the surface (Figures 6 and 7).

$\text{NO}_3^- + \text{NO}_2^-$. Nitrate + nitrite concentration ranges were centered at or below approximately 10 µg/L across all parks (Figures 6 and 7). The exception was at the mouth of the Honokohau Small Boat Harbor, where concentrations up to 166 µg/L were observed.

Chlorophyll. Chlorophyll was frequently not detected at all parks (Figures 6 and 7). At Kaloko-Honokōhau NHP outlying concentrations of chlorophyll were observed in the center and northern portion of the area, with the highest concentrations observed at the northern most stations closest to the golf course.

pH. Waters at all parks showed consistent pH values of 8.15 (Figures 6 and 7). More alkaline conditions coupled with higher turbidity suggesting minor algal blooms were observed at Kaloko-Honokōhau NHP, but not included in summaries of data ranges (Appendix D).

Turbidity. All waters in the marine near shore environments of PACN parks had very low turbidity with values approaching 0 NTU (Figures 6 and 7). Variability in turbidity at National Park of American Samoa Ofu unit may have been caused by wave action suspending material in a shallow area. Higher than typical turbidity was observed at Kaloko-Honokōhau NHP throughout 2010.

Oxygen saturation. All waters in the marine near shore environments of PACN parks were well oxygenated, with saturations of approximately 105% (Figures 6 and 7). Both units of National Park of American Samoa displayed higher levels of supersaturation, likely the result of wave action.

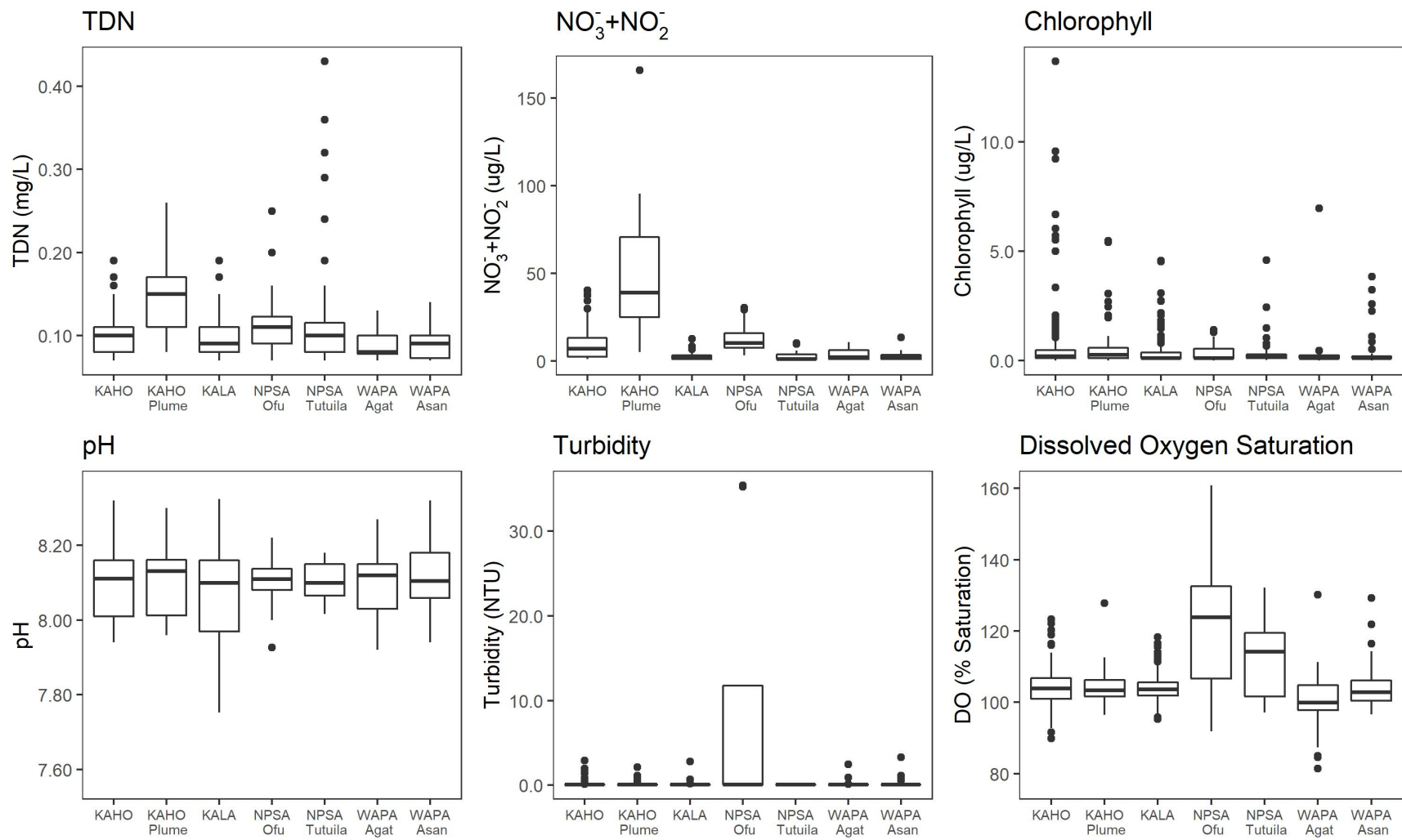


Figure 6. Distribution of selected marine water quality parameters measured during typical conditions at the surface in PACN parks, 2008–2015.

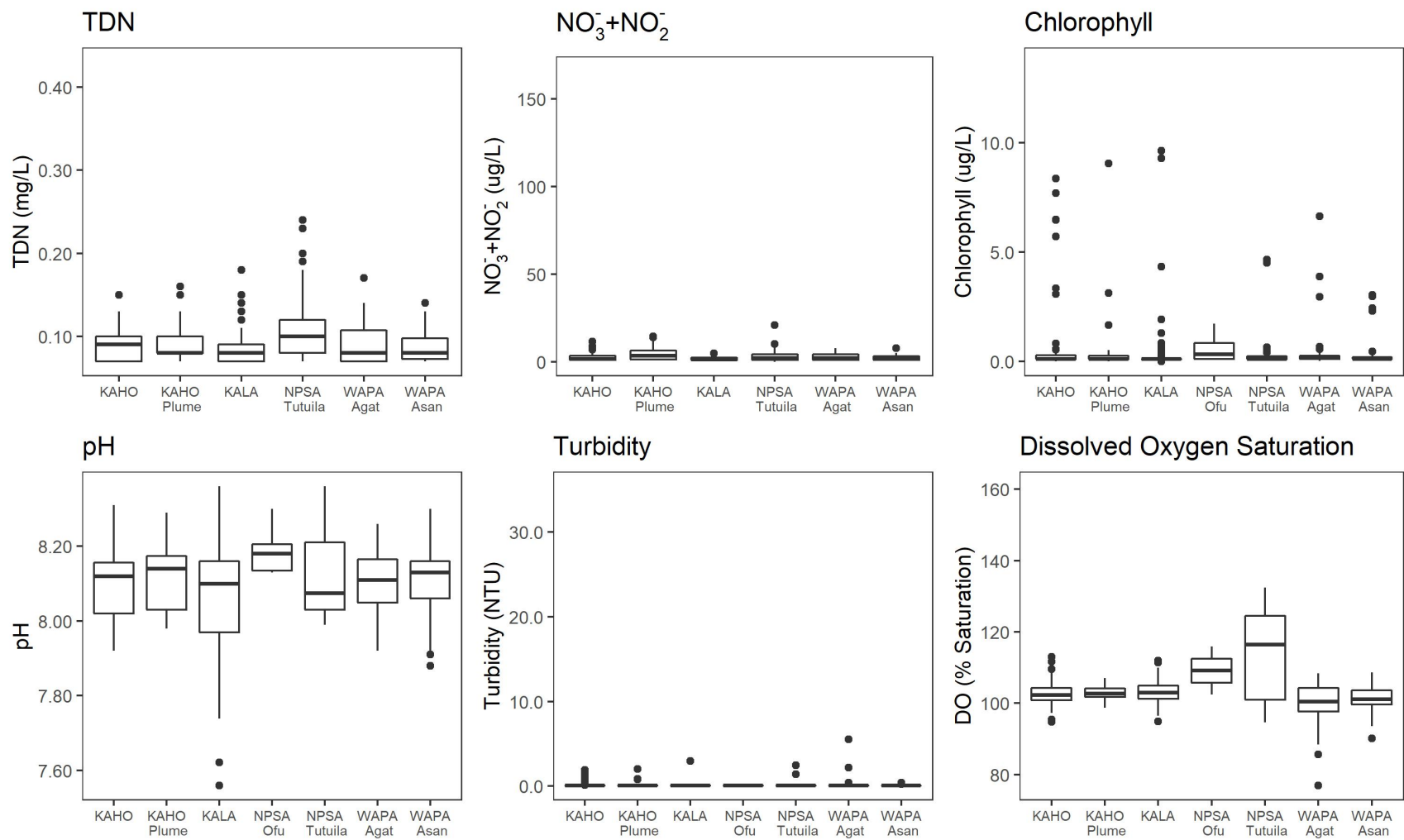


Figure 7. Distribution of selected marine water quality parameters measured during typical conditions near the bottom in PACN parks, 2008–2015.

Trends

Very few trends were observed over the study period (Table 3; Figures 8–13; Appendix C). At Kalaupapa NHP, TDN decreased in 2014 and then remained low (Figure 9). At War in the Pacific NHP Agat unit, relatively high concentrations of chlorophyll were observed at the beginning of the observation period (Figure 11). Salinity decreased by 1–2 ppt at all park areas except Tutuila (NPSA) and Agat (WAPA) (Figures 8–10 and Figure 13). At Kaloko-Honokōhau NHP temperature in marine waters of increased from 2009 to 2015 (Figure 8), with the lowest observed temperatures occurring in 2009, and the highest observed temperatures occurring in 2015 (Figure 8). Temperature also increased at Kalaupapa NHP (Figure 9). Data censoring rates are presented in Appendix E.

Table 3. Trends detected in marine water quality parameters at PACN national parks. Arrows indicate direction of trend significant at $p < 0.05$.

Parameter	Kaloko-Honokōhau NHP	Kalaupapa NHP	War in the Pacific NHP, Asan	War in the Pacific NHP, Agat	NP of American Samoa, Tutuila	NP of American Samoa, Ofu
TDN	—	↓	—	—	—	—
TDP	*	*	*	*	*	*
$\text{NO}_3^- + \text{NO}_2^-$	—	—	—	—	—	—
Chlorophyll	*	—	*	↓	—	*
Oxygen	—	—	—	—	—	—
pH	—	—	—	—	—	—
Salinity	↓	↓	↓	—	—	↓
Temperature	↑	↑	—	—	—	—
Turbidity	*	*	*	*	*	*

* = More than 50% censored data due to non-detection. High rates of data censoring reduce confidence that the remaining uncensored data represents the true distribution of actual values present in the system.

Note Concerning National Park of American Samoa

Missing data limited analyses of marine water quality at National Park of American Samoa. Several sampling events were flagged as unreliable during quality assurance checks, due primarily to equipment failures or collection errors that resulted in erroneous values and were consequently excluded from analyses. The censored dataset for nutrients at Tutuila included data for only one quarter in 2009, 2010, and 2013 and two quarters in 2011 and 2015. No second quarter data were included in the dataset, and the only dry season record included was for 2011. The censored dataset for YSI parameters at Tutuila included data for only six quarters over seven years. At Ofu, the censored dataset included more sampling events than Tutuila, but only one sampling event was from the first quarter and only one quarter was represented in 2015. Due to the number of missing values, neither season nor quarter could be included as a factor in the mixed model analyses for Ofu or Tutuila, and the results of the seasonality analyses should be used cautiously. At Tutuila, coverage of

temporary sites was not sufficient to compare data from surface fixed and temporary sites. The NPSA dataset also lacked sufficient replication to run the mixed model and seasonal Mann-Kendall test, necessitating use of Mann-Kendall only.

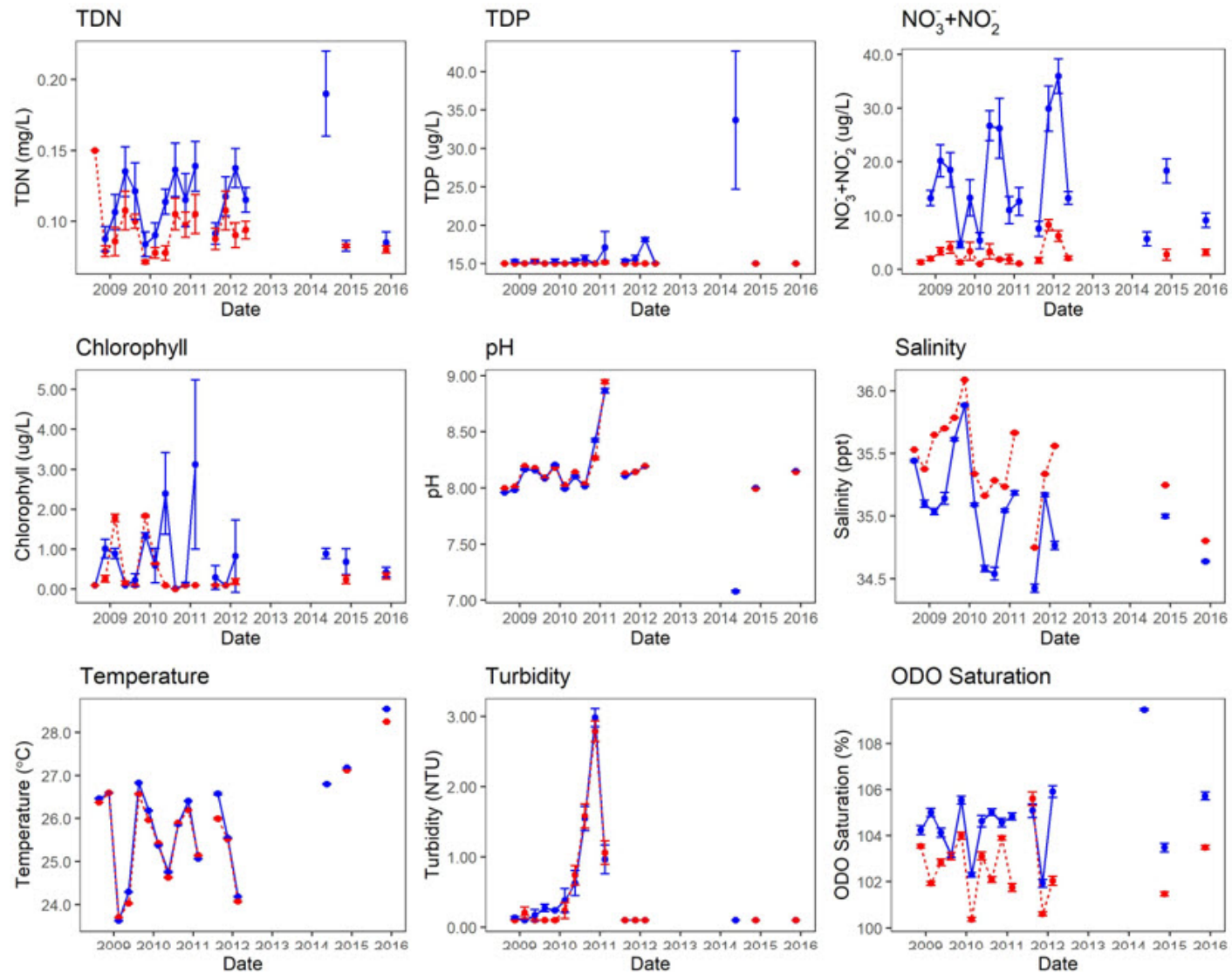


Figure 8. Water quality parameters in marine waters of Kaloko-Honokōhau National Historical Park, 2009–2015. Blue = surface, red = bottom. Error bars are the 95% C.I.

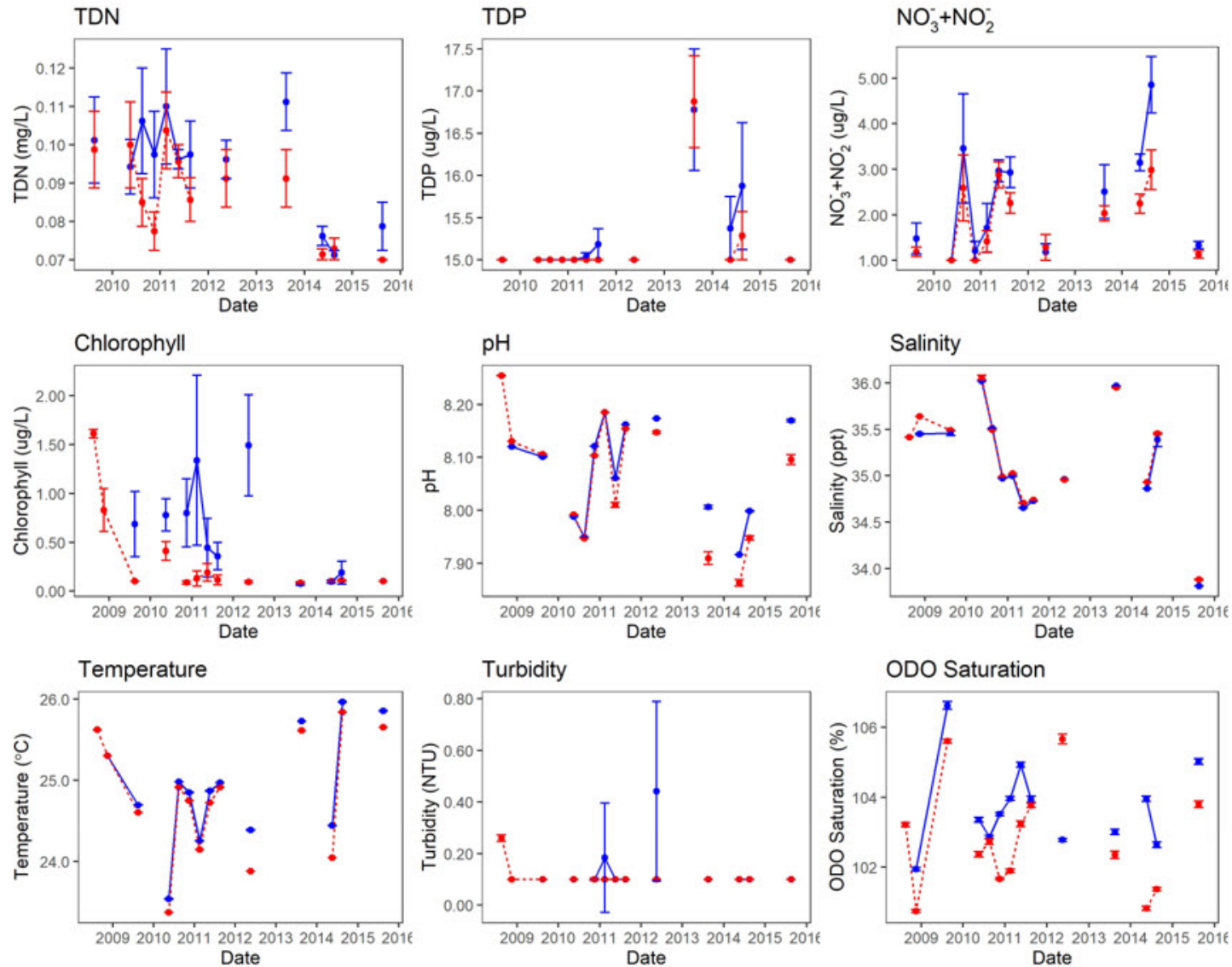


Figure 9. Water quality parameters in marine waters of Kalaupapa National Historical Park, 2009–2015. Blue = surface, red = bottom. Error bars are the 95% C.I.

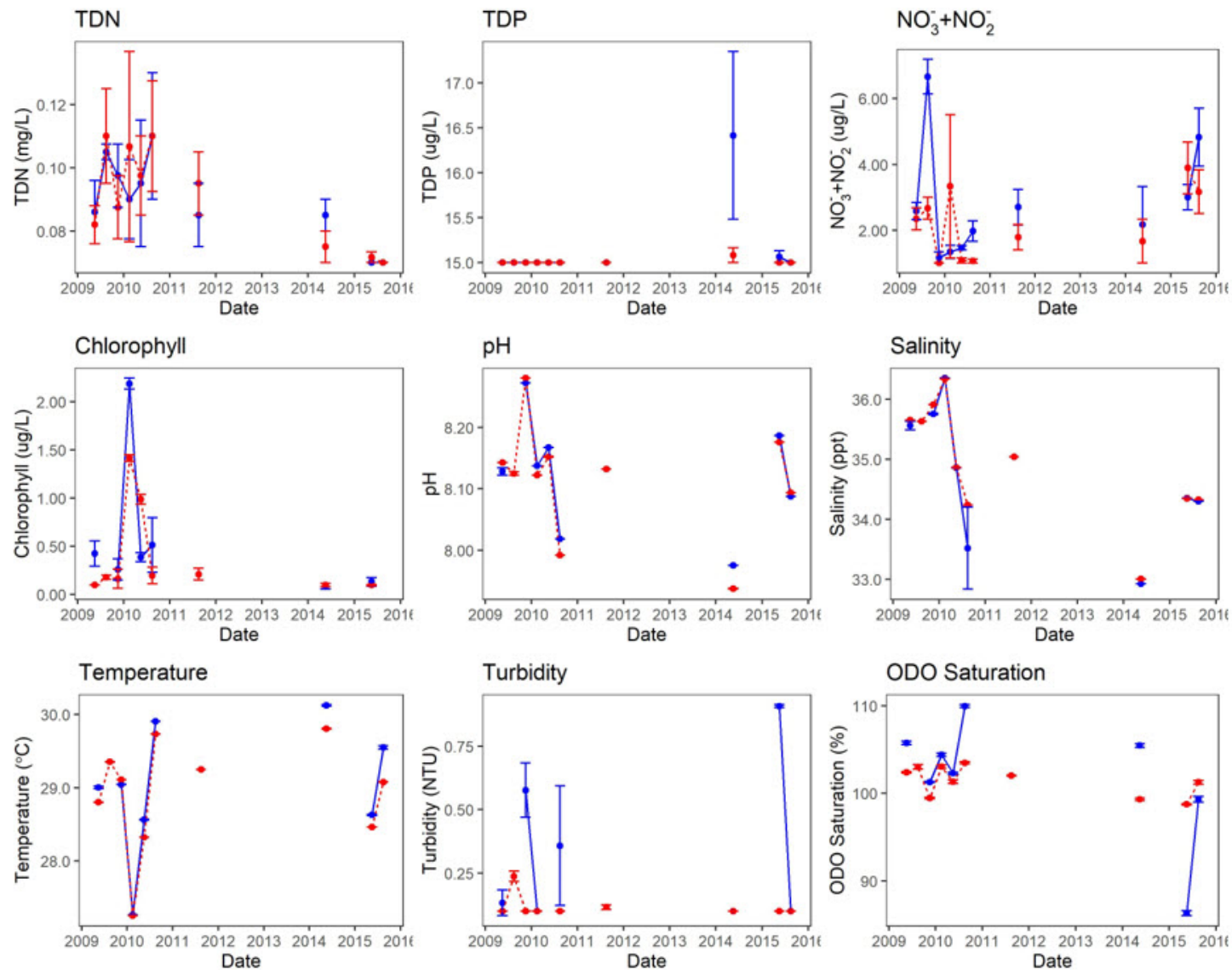


Figure 10. Water quality parameters in marine waters of War in the Pacific National Historical Park, Asan Marine Unit, 2009–2015. Blue = surface, red = bottom. Error bars are the 95% C.I.

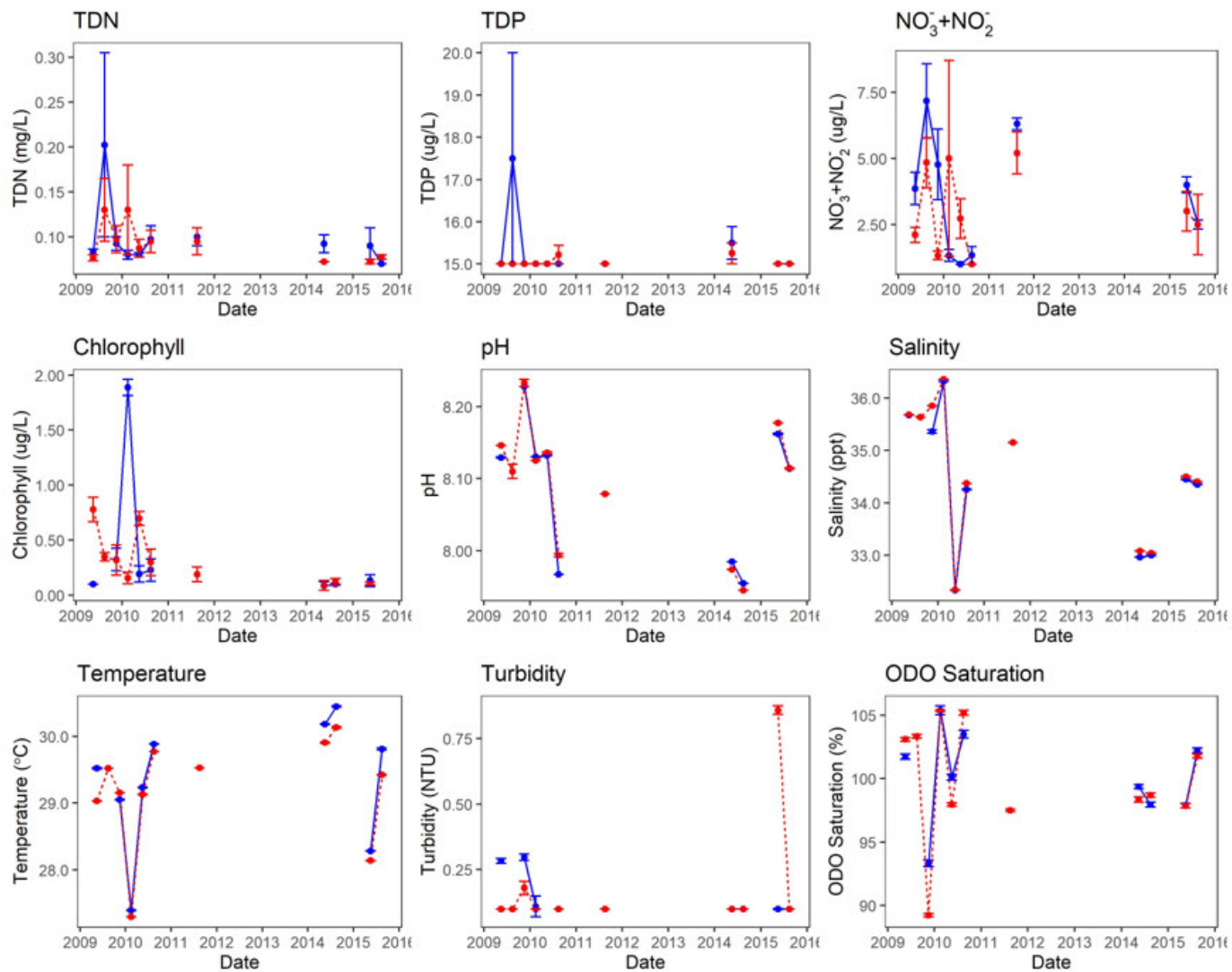


Figure 11. Water quality parameters in marine waters of War in the Pacific National Historical Park, Agat Marine Unit, 2009–2015. Blue = surface, red = bottom. Error bars are the 95% C.I.

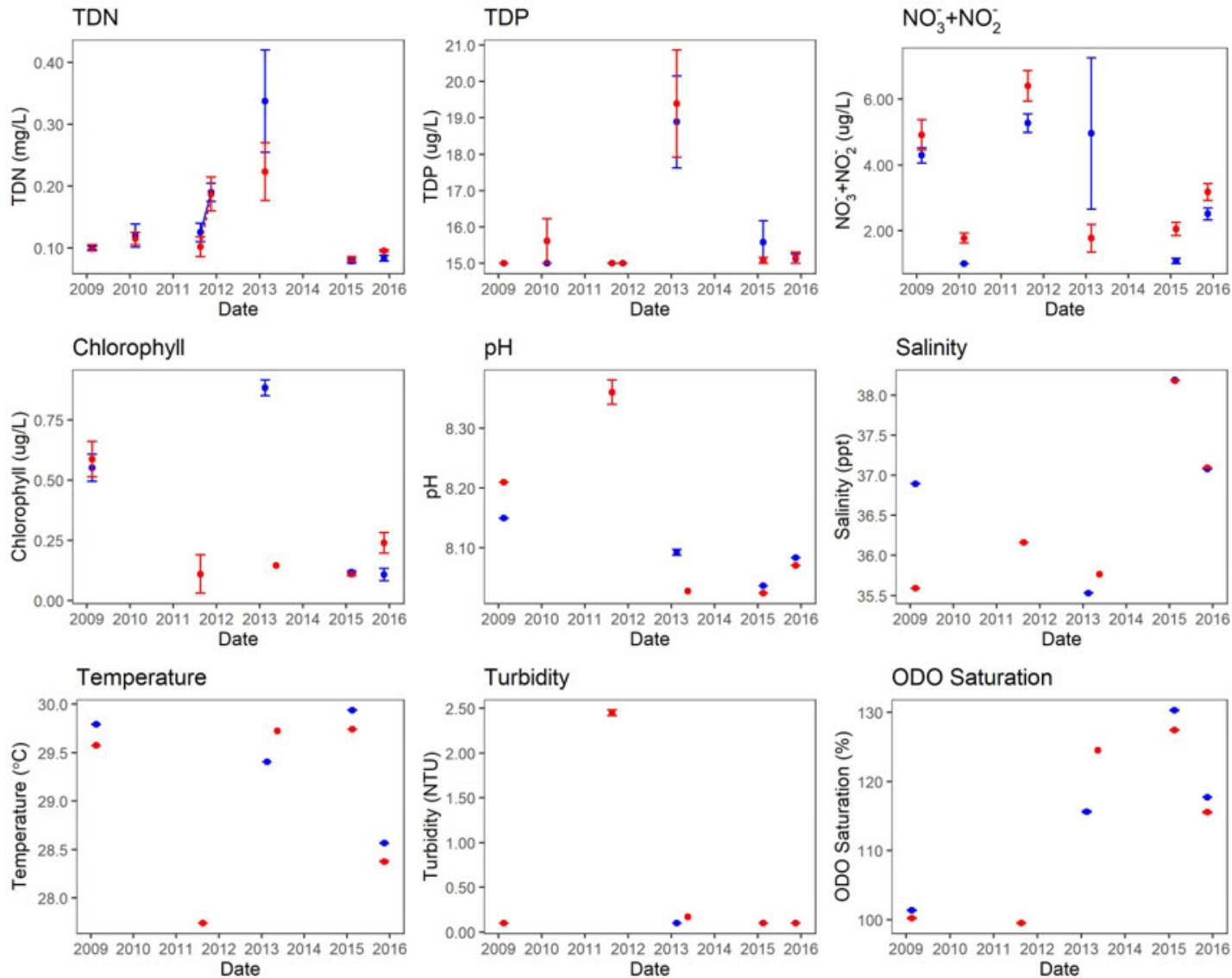


Figure 12. Water quality parameters in marine waters of National Park of American Samoa, Island of Tutuila, 2009–2015. Blue = surface, red = bottom. Error bars are the 95% C.I.

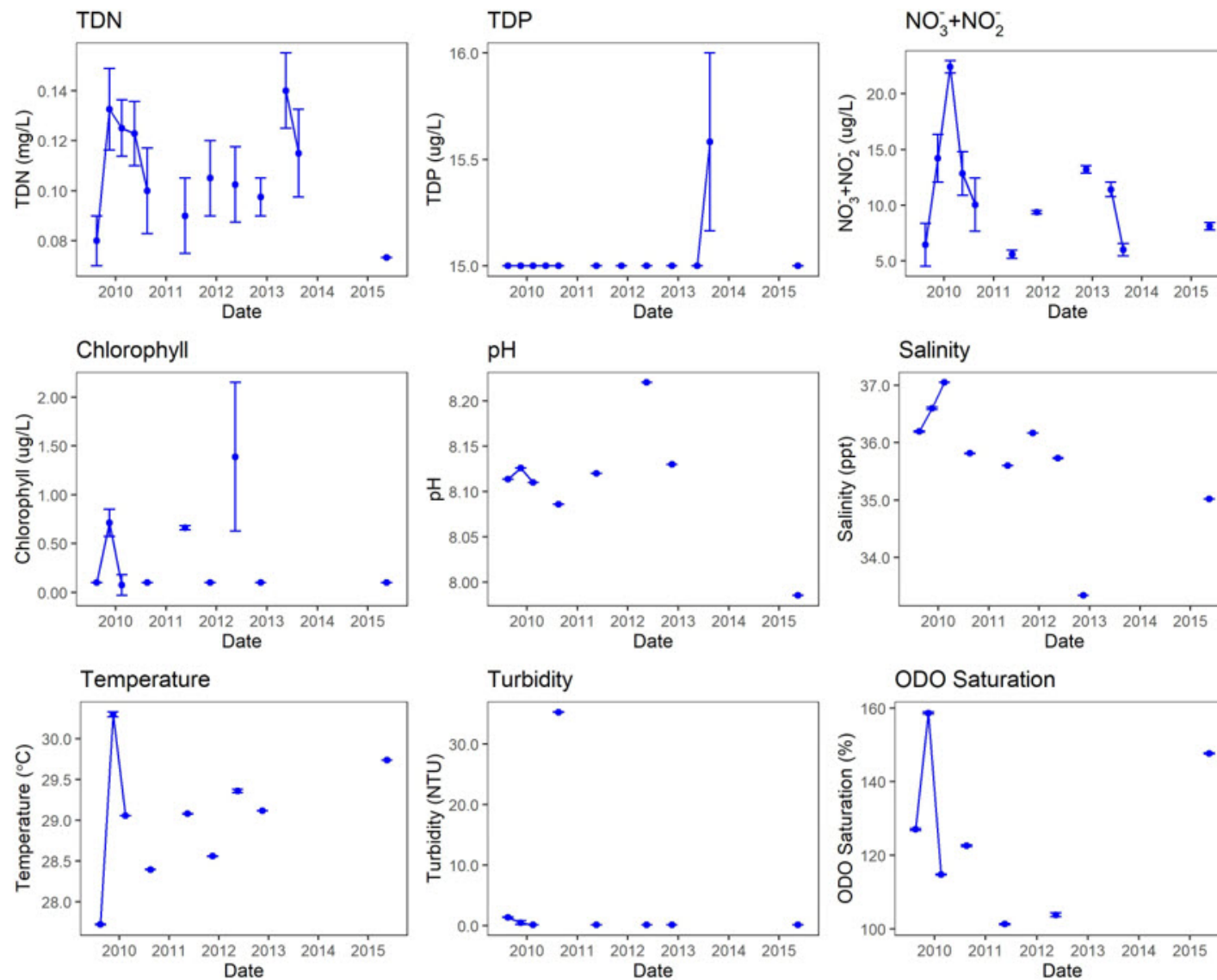


Figure 13. Water quality parameters in surface marine waters of National Park of American Samoa, Island of Ofu, 2009–2015. Error bars are the 95% C.I.

Spatial Patterns

The color ramp used in the display of spatial interpolations blends five distinct colors to aid interpretation, corresponding to points along the scale regardless of absolute values: black = 0% of the scale, blue = 25%, green = 50%, yellow = 75%, and white = 100% (Figures 14–17). No consistent spatial patterns were observed at Kalaupapa NHP, War in the Pacific NHP, or National Park of American Samoa. Complete sets of maps are available in data reports for all parks (Raikow, Farahi, Kichman, and McCutcheon 2017; Raikow, Farahi, McCutcheon et al. 2017; Raikow, Farahi, McCutcheon, Fuiava et al. 2017; Raikow, Farahi, McCutcheon, and Kichman 2017). Selected results are presented here. At Kaloko-Honokōhau NHP higher concentrations of TDP, lower salinity, and lower temperatures relative to other sites within a sampling event were regularly observed at the surface near the mouth of Honokohau Small Boat Harbor (Figures 14–15). Near-bottom conditions were frequently spatially homogeneous across the study area (Figure 16). In the last quarter of 2010, high pH was observed at the surface near the mouth of the Honokohau Small Boat Harbor at Kaloko-Honokōhau NHP, and the highest turbidity measured at this park occurred across the study area (Figure 17; Raikow, Farahi, Kichman, and McCutcheon 2017). In following quarter, relatively high pH was observed across the study area, surface oxygen saturation was unusually evenly distributed across the study area, and chlorophyll was relatively high across the study area (Raikow, Farahi, Kichman, and McCutcheon 2017).

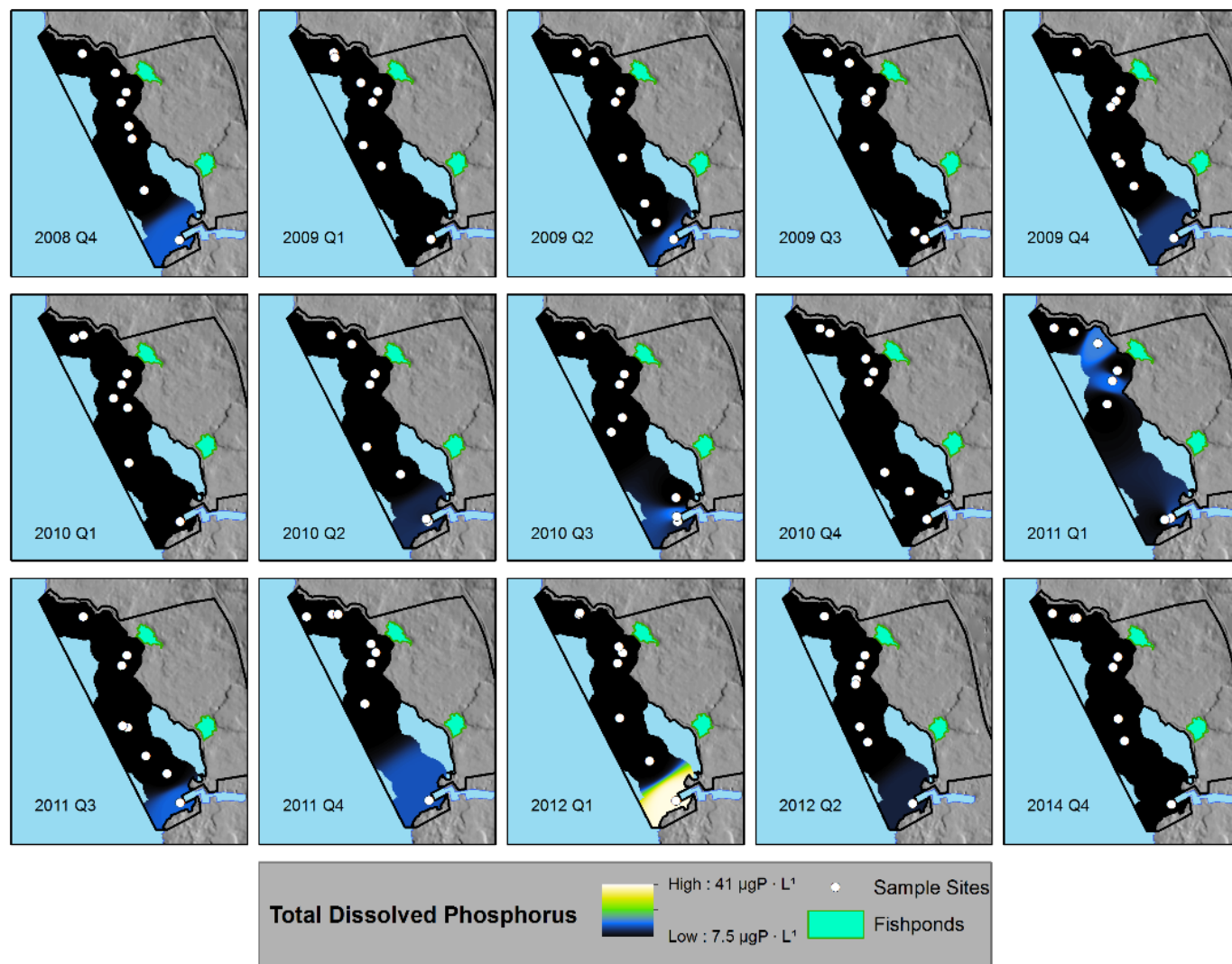


Figure 14. Spatial distribution of surface total dissolved phosphorus in marine waters of Kaloko-Honokōhau National Historical Park illustrating multiple observations of increased nutrient concentrations near the Honokohau Harbor mouth.

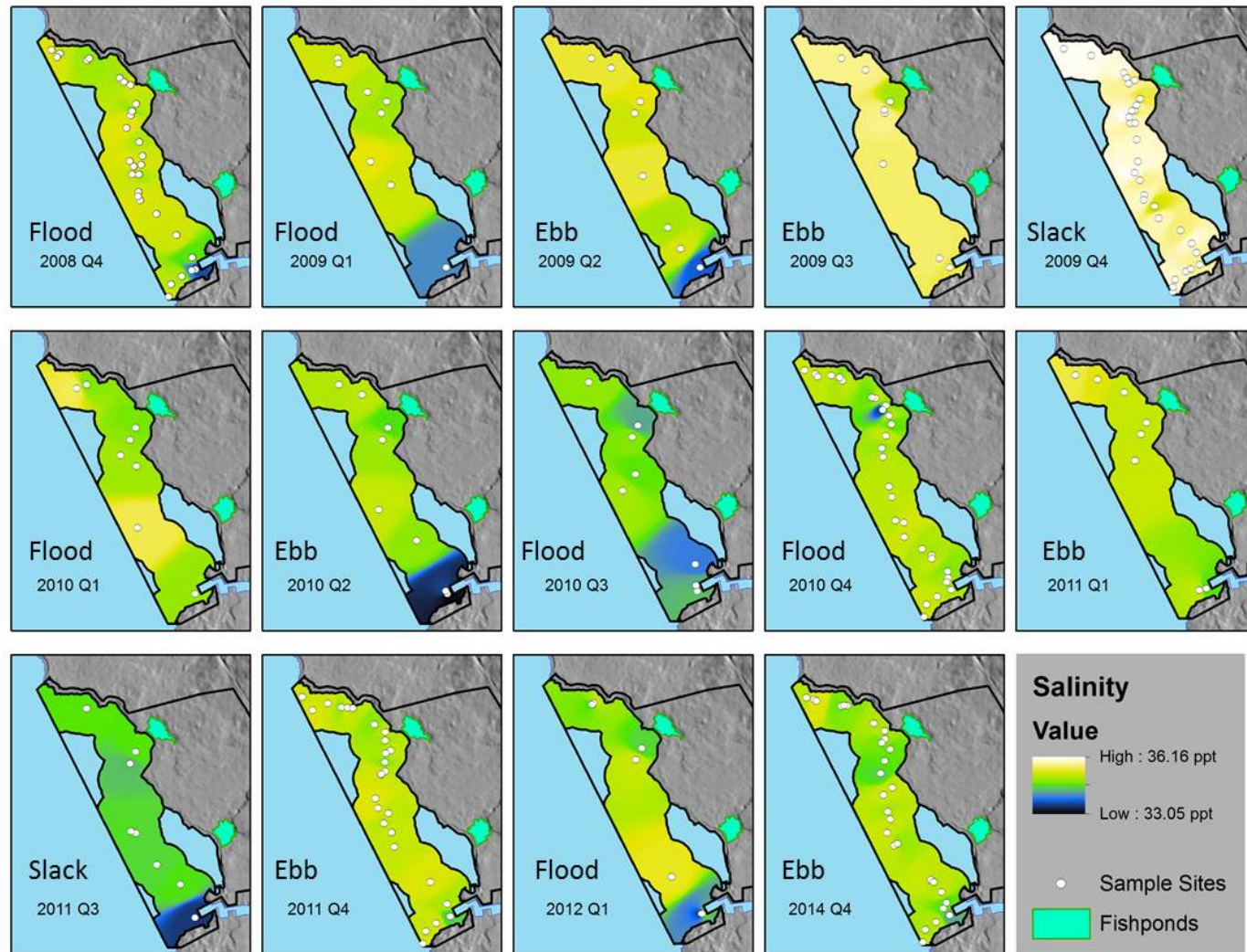


Figure 15. Spatial distribution of surface salinity in marine waters of Kaloko-Honokōhau National Historical Park illustrating multiple observations of less saline water at the mouth of Honokohau Harbor.

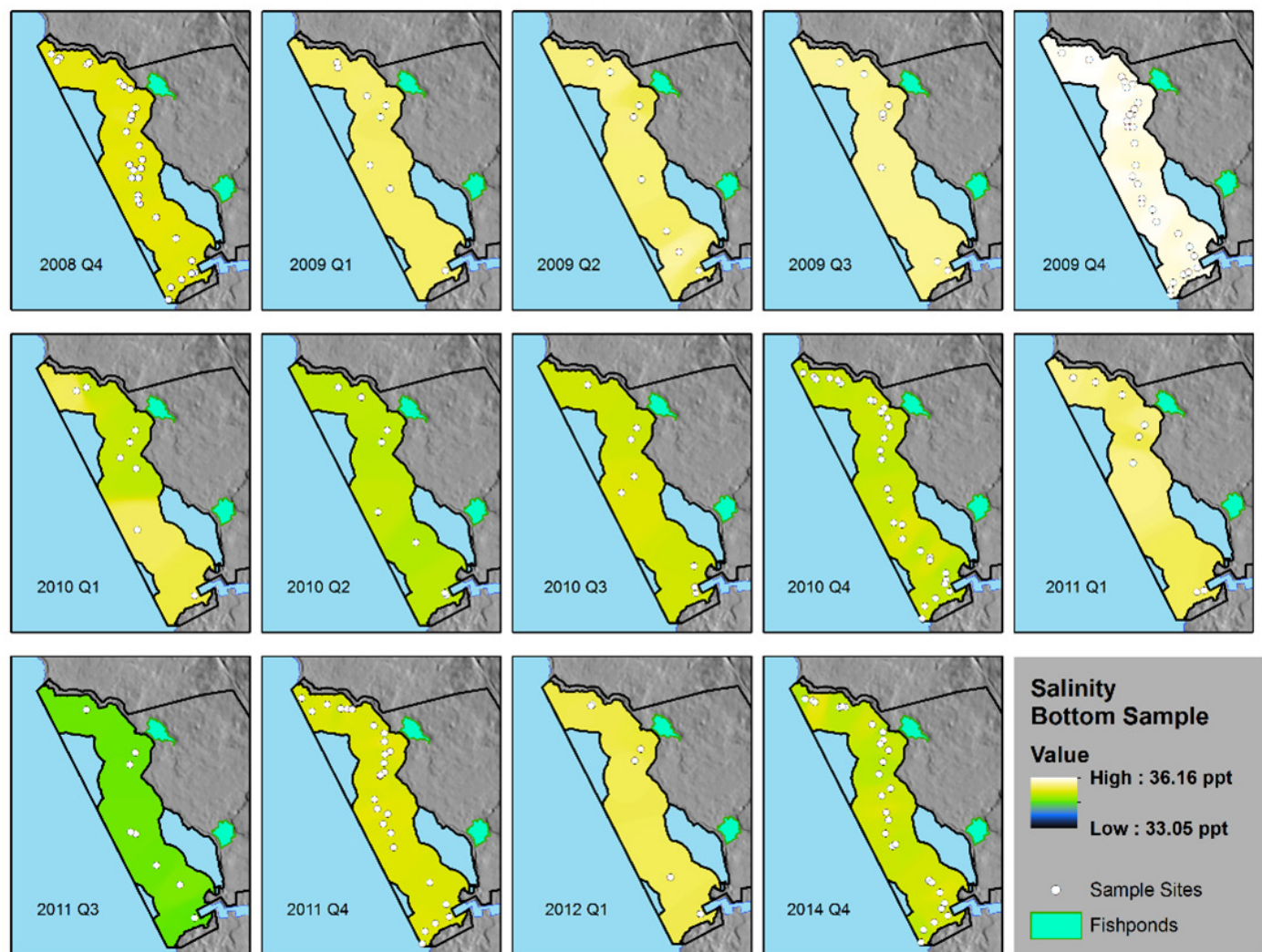


Figure 16. Spatial distribution of bottom salinity in marine waters of Kaloko-Honokōhau National Historical Park illustrating spatially homogenous conditions in contrast to surface conditions.

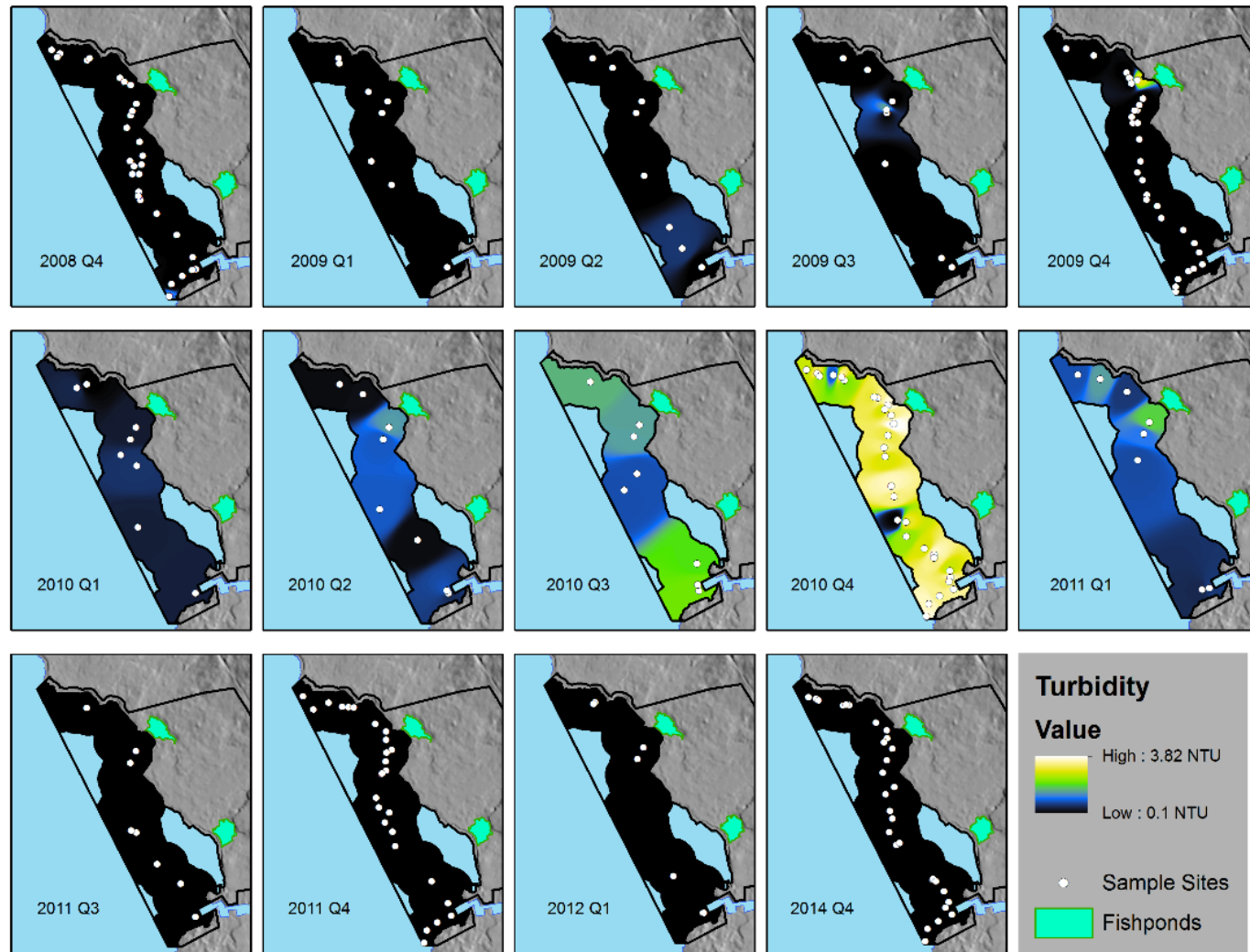


Figure 17. Spatial distribution of surface turbidity in marine waters of Kaloko-Honokōhau National Historical Park illustrating a high-turbidity event in 2010 Q4.

Dissolved and Particulate Nutrient Fractions

The dissolved fraction dominated nutrients at all parks, e.g. all medians were at or above 98%. (Table 4). Some distributions, primarily WAPA, were affected by left-skewed data, caused by a greater proportion of particulates present during an individual sampling event. Instances of high particulates were sporadic and not consistent across parks and sampling sites. Near-normal distributions of results centered on high dissolved proportions coupled with clustered left-skewed data indicated bi-modality, meaning samples were collected both at times of low-particulate abundance and when particulate abundance was high (Appendix F).

Table 4. Summary of the distribution of dissolved nutrient proportions (%) phosphorus (P) and nitrogen (N) in the marine waters of selected pacific island parks.

Statistic	P KAHO	N KAHO	P KALA	N KALA	P WAPA	N WAPA
Maximum	100	100*	100*	100*	100	100*
3rd Quartile	100	100*	100	100	100	100*
Mean	98	100*	100*	94	75	100*
Median	100	100*	100	98	100	100
1st Quartile	100	100	100	83	57	76
Minimum	84	97	61	62	5	56

* Values above 100% are reported here as the maximum, or 100%.

Seasonality

Temperature showed strong evidence for seasonality, with significant results in most tests at all parks except Kalaupapa NHP (Table 5, Appendix B). Chlorophyll showed evidence of seasonality at War in the Pacific NHP. See Appendix B for individual statistical test results.

Table 5. Number of test statistical test permutations with significant seasonality results (maximum = 4) for all PACN parks.

Parameter	KAHO	KALA	NPSA, Tutuila	NPSA, Ofu (max = 2)	WAPA, Asan	WAPA, Agat
TDN	1	–	–	–	–	–
TDP	1	–	–	–	–	–
NO ₃ [–] + NO ₂ [–]	–	1	–	–	–	–
Chlorophyll	2	–	1	–	4	3
Oxygen	–	2	1	–	–	–
pH	–	–	–	–	–	–
Salinity	–	–	–	–	–	–
Temperature	4	2	4	2	3	3
Turbidity	–	–	–	–	–	–

Surface and Near-bottom Sample Correlation

Parameters measured at the surface and 2–3m above the bottom (“near-bottom” samples) were highly correlated, many with $r \geq 0.99$ (Table 6). Data censoring obscured temporal patterns in some parameters precluding analysis of correlation. Dissolved oxygen saturation was less correlated than were other parameters. This is consistent with simple stratification of surface and near bottom samples in nearshore waters. Wave action at the surface will allow more oxygen to be dissolved independently of oxygen near the bottom. Nutrients in surface and near bottom waters at WAPA were less well correlated than at other parks. Frequent censoring of TDP, chlorophyll, and turbidity affected correlations, reducing statistical significance of those individual tests.

Table 6. Correlation coefficients (R) for surface and bottom samples in marine areas of PACN parks.

Parameter	KAHO	KALA	NPSA, Tutuila	WAPA, Asan	WAPA, Agat	WAPA, units combined
TDN	0.85	0.87	0.93	0.65	0.43	0.43
TDP	c	0.98	0.99	1.00	c	0.46
NO ₃ ⁻ + NO ₂ ⁻	0.78	0.95	0.62	0.47	0.36	0.46
Chlorophyll	c	c	i	0.86	c	0.45
Oxygen	0.56	0.51	i	0.71	0.97	0.80
pH	0.97	0.96	i	0.99	0.99	0.99
Salinity	0.83	0.99	i	0.98	0.99	0.99
Temperature	0.99	0.98	i	0.99	0.98	0.99
Turbidity	0.99	i	i	i	0.68	i

c = Temporal pattern obscured by a high rate of data censoring.

i = Insufficient data.

Comparison of Fixed and Temporary Sites

With few exceptions, the means of water quality parameters collected at surface fixed sites were the same as means of water quality parameters collected at surface temporary sites at all parks (Table 7). Absolute differences between means, when significant at $p < 0.05$, were very small, and not substantially different over time (Appendix G).

Table 7. Summary of Mann-Whitney tests (p) comparing data collected at surface fixed and temporary sites.

Parameter	KAHO, Plume area	KAHO, Non-plume area	KALA	NPSA, Tutuila	NPSA, Ofu	WAPA, Asan	WAPA, Agat
TDN	0.46	0.08	0.26	i	0.27	0.10	0.31
TDP	0.49	0.90	0.34	i	0.86	0.82	0.91
NO ₃ ⁻ + NO ₂ ⁻	0.55	*	0.37	i	0.07	0.66	0.81
Chlorophyll	0.52	0.52	0.27	i	0.71	0.26	0.64
Oxygen	0.85	*	0.30	i	0.80	0.31	0.42
pH	0.98	0.42	0.83	i	0.67	0.30	0.29
Salinity	0.93	0.42	0.39	i	0.23	0.85	0.67
Temperature	0.51	0.92	0.86	i	0.87	0.63	0.95
Turbidity	0.28	0.93	0.09	i	*	0.09	0.64

i = insufficient coverage of temporary sites.

* = $p < 0.05$.

Climatological Context

Over the course of the study period, one complete ENSO cycle occurred, and another began (Figure 18). According to the NOAA Oceanic Niño Index, the ENSO cycle moved from La Niña conditions in 2008 to El Niño in 2009–2010, back to La Niña, stayed in the neutral condition from 2012 to 2014, and moved into El Niño in 2015 (NOAA 2018). Rainfall response at all national parks was generally consistent with regional ENSO patterns.

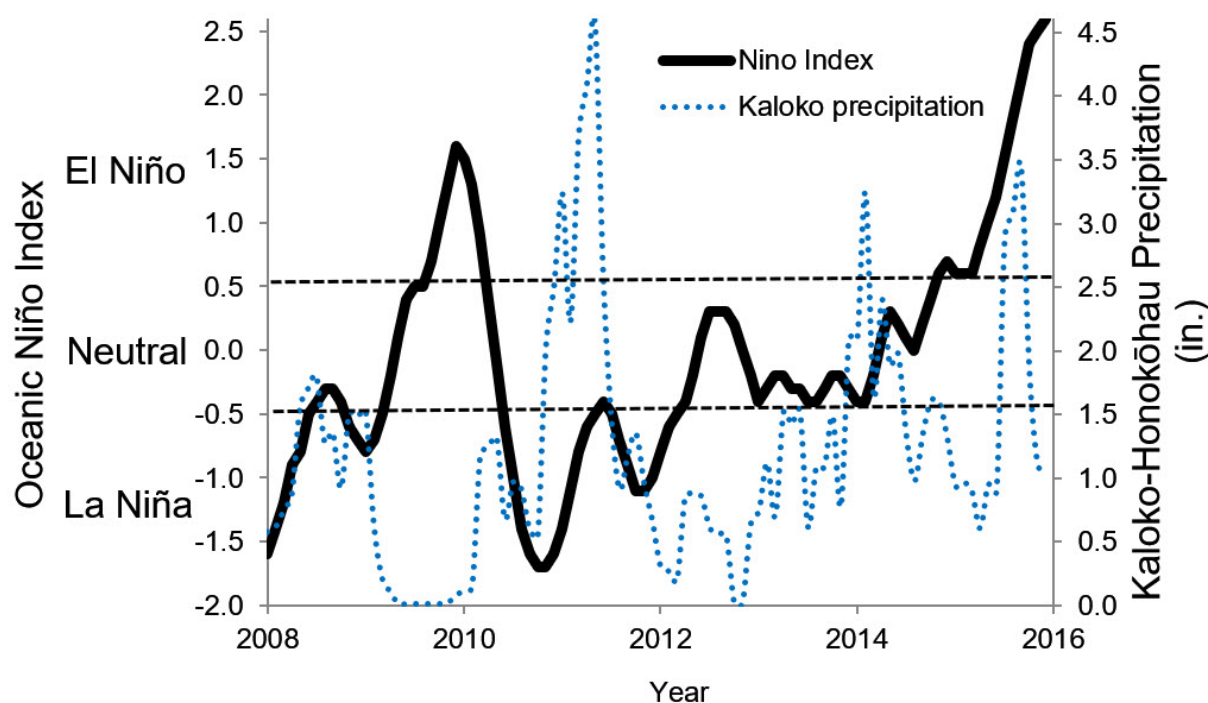


Figure 18. Oceanic Niño Index (NOAA 2018) compared to rainfall at Kaloko-Honokōhau National Historical Park (using LOESS smoothing, FA667668 Kaloko Honokohau Hawaii).

Rainfall at Kaloko-Honokōhau NHP varied greatly from 2008–2015 (Figure 18). Low rainfall occurred in late 2009 during the peak of an El Niño phase, and increased greatly immediately afterward. Such rainfall patterns were consistent with general ENSO effects on Hawaii (Rupic et al. 2018). Off-shore salinity peaked at the time of low rainfall in early 2010 (Figure 19). Off-shore salinity was always negatively correlated with precipitation, as expected (Table 8). The strongest correlations were obtained using the mean of the third and fourth months back for both surface and bottom samples ($r = -0.65$ and $r = -0.75$, respectively, Table 8). While salinity was correlated to some degree with concurrent precipitation, or “current month,” for both surface and near-bottom samples ($r = -0.47$ and $r = -0.46$, respectively, Table 8), salinity was weakly correlated with the previous month’s precipitation for both surface and near-bottom samples ($r = -0.05$ and $r = -0.10$, respectively, Table 8). Correlations using mean precipitation over the current and previous months were weak compared to correlations using means that included precipitation from three and four months back.

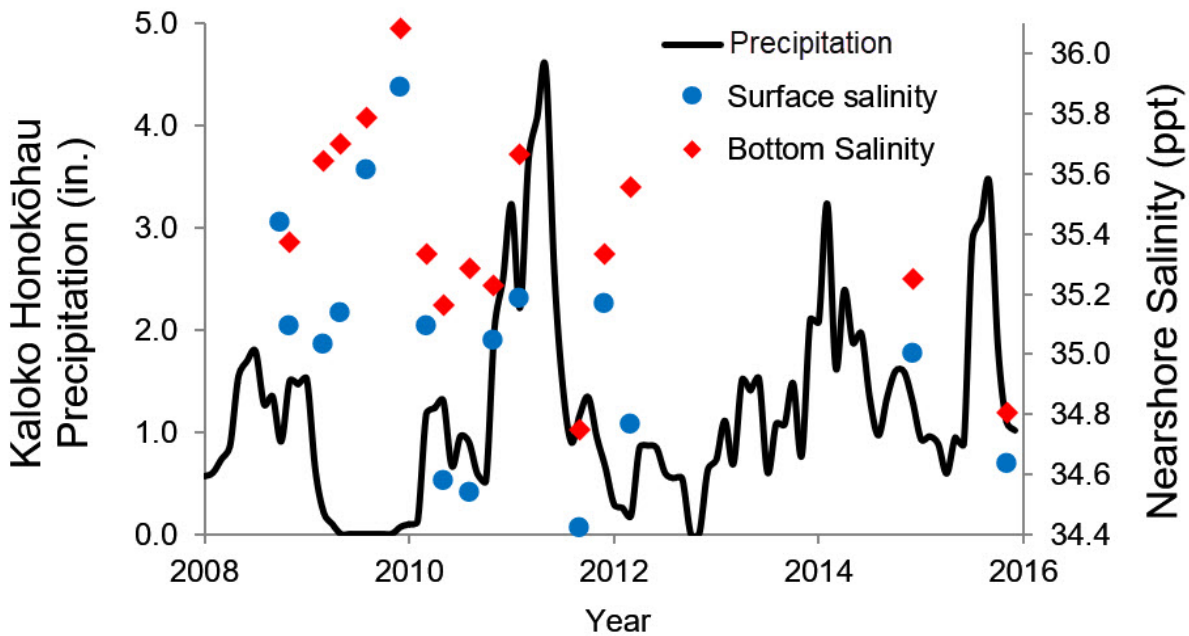


Figure 19. Nearshore salinity compared to rainfall at Kaloko-Honokōhau National Historical Park (FA667668 Kaloko-Honokōhau Hawaii).

Table 8. Correlation (r) of nearshore salinity and monthly average precipitation at Kaloko-Honokōhau National Historical Park (KAHO).

Precipitation month compared to current salinity	Surface	Bottom
Current	-0.47	-0.46
Previous	-0.05	-0.10
2nd month back	-0.40	-0.60
3rd month back	-0.60	-0.49
4th month back	-0.42	-0.45
Mean of current and previous	-0.29	-0.31
Mean of current and previous 2	-0.41	-0.54
Mean of current and previous 3	-0.62	-0.70
Mean of current and previous 4	-0.63	-0.71
Mean of 2nd and 3rd months back	-0.29	-0.45
Mean of 2nd, 3rd, and 4th months back	-0.54	-0.64
Mean of 3rd and 4th months back	-0.65	-0.75

Rainfall decreased during the El Niño phase at Kalaupapa NHP but did not increase to the same extent during later times as observed Kaloko-Honokōhau NHP (Figure 20). Guam’s response to

ENSO was similar to the response of other Pacific regions, with more rain at early stages of El Niño development and less rain thereafter (Rupic et al. 2018). Exceptionally high rain fell in Guam in early 2010 at the peak of the El Niño phase (Figure 21). Effects of ENSO were not readily apparent at National Park of American Samoa compared to other parks. Tutuila rainfall was much less variable over the monitoring period than at other parks and did not correspond to ENSO conditions (Figure 22).

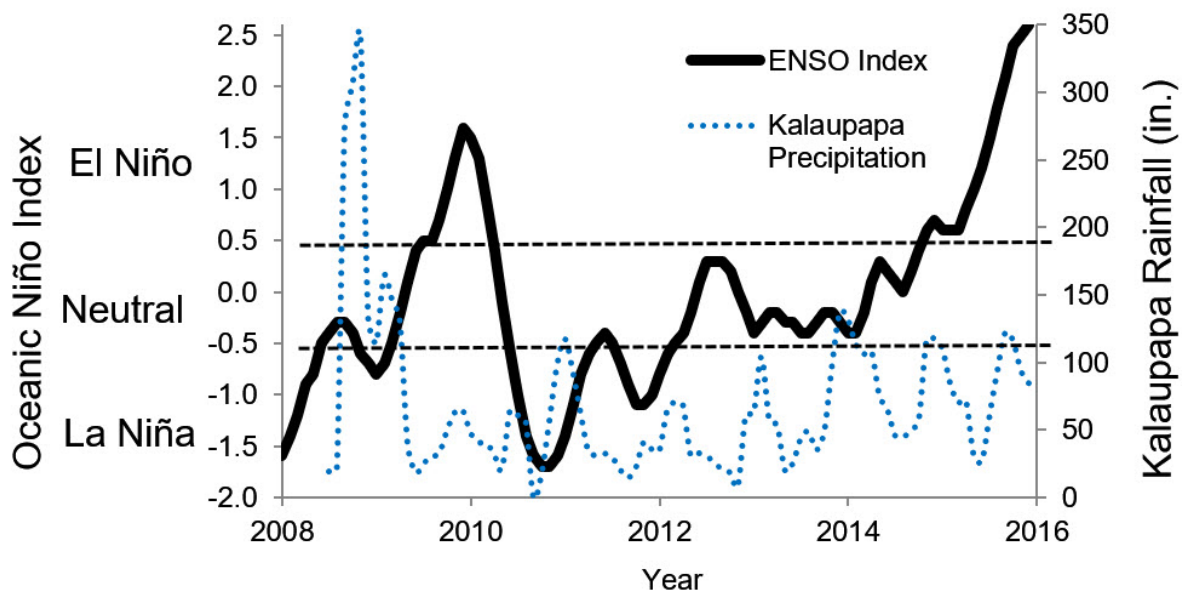


Figure 20. Oceanic Niño Index compared to total monthly rainfall at Kalaupapa National Historical Park.

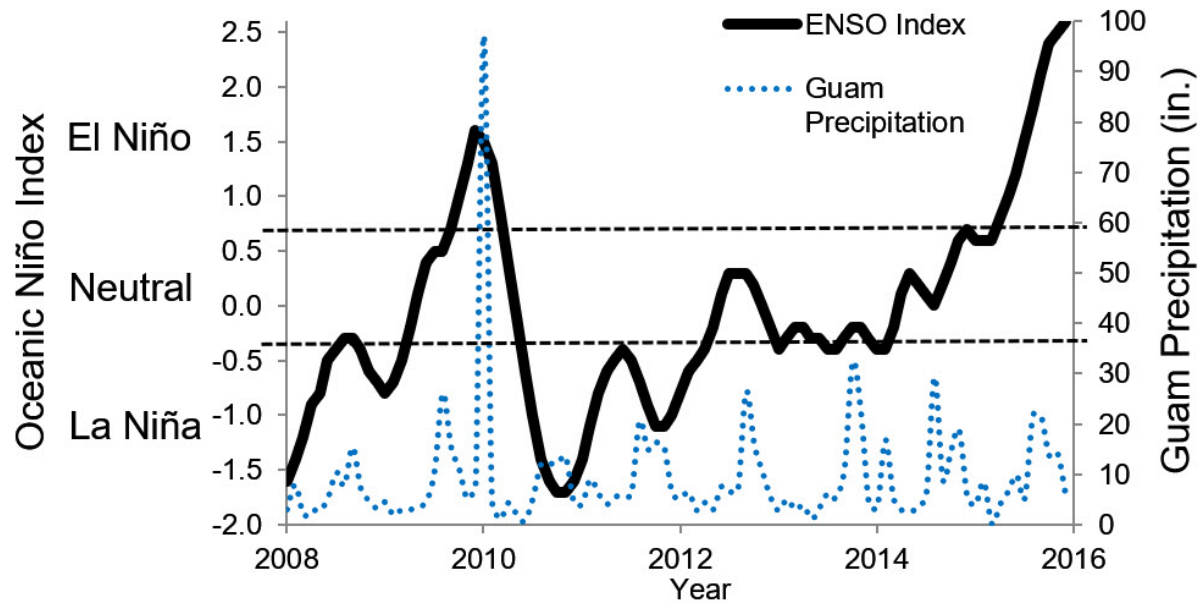


Figure 21. Oceanic Niño Index compared to total monthly rainfall at War in the Pacific National Historical Park.

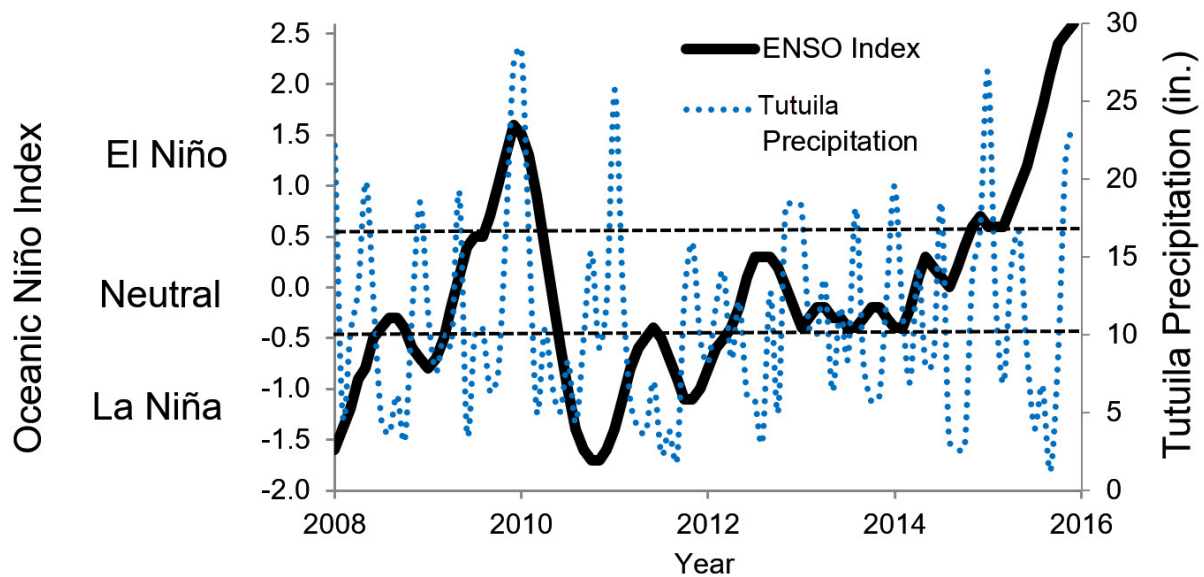


Figure 22. Oceanic Niño Index compared to total monthly rainfall at National Park of American Samoa.

Summary of results by park

Kaloko-Honokōhau National Historical Park

- Nutrient concentrations were unremarkable and consistent with previous studies. (Figure 8).
- SGD plumes were detected at the surface especially near Honokohau Small Boat Harbor (Figures 14, 15).
- Unusual conditions possibly including an algal bloom or blooms occurred in late 2010 and early 2011 concurrent with heavy rainfall (Figure 17).
- A decreasing trend was observed for salinity and increasing trend for temperature (Table 3).
- Nutrients were dominated by dissolved fractions (Table 4).
- Temperature showed strong evidence of seasonality while TDN, TDP and chlorophyll showed weak evidence of seasonality (Table 5).
- Surface measurements were highly correlated with bottom measurements, except for TDP and chlorophyll due to data censoring (Table 6).
- Salinity was negatively correlated with terrestrial precipitation during the previous month and precipitation that fell three and four months prior (Table 8).
- Data censoring rates were very high for TDP, chlorophyll, and turbidity (Appendix E).
- Tidal stage affected measurements.
- The salinity trend can be explained by the timing of ENSO phases.
- The temperature trend can be explained by the timing of ENSO phases and/or may be an artifact of variation.

Kalaupapa National Historical Park

- Nutrient concentrations were unremarkable and consistent with previous studies (Figure 9).
- TDN showed a decreasing trend in the form of step-change (Figure 9).
- Temperature showed an increasing trend (Table 3).
- Salinity showed a decreasing trend (Table 3).
- Nutrients were dominated by dissolved fractions (Table 4).
- Temperature showed strong evidence of seasonality (Table 5).
- Surface measurements were highly correlated with bottom measurements, except for chlorophyll due to data censoring (Table 6).
- Data censoring rates were very high for TDP and turbidity (Appendix E).
- No SGD or surface water plumes were detected.
- No spatial patterns were observed.
- The temperature and salinity trend can be partially explained by the timing of ENSO phases.

War in the Pacific National Historical Park

- Nutrient concentrations were unremarkable and consistent with previous studies of pacific islands (Figure 10, 11).
- Salinity at Asan showed a decreasing trend (Table 3).
- Chlorophyll at Agat showed a decreasing trend (Table 3).
- Nutrients were dominated by dissolved fractions (Table 4)
- Temperature and chlorophyll showed strong evidence of seasonality (Table 5).
- Surface measurements were highly correlated with bottom measurements (Table 6).
- Data censoring rates were very high for TDP and turbidity (Appendix E).
- No SGD plumes were detected.
- The salinity trend can be explained by the timing of rain events.

National Park of American Samoa

- Nutrient concentrations were unremarkable and consistent with previous studies of Pacific islands (Figures 12, 13).
- Salinity at Ofu showed a decreasing trend (Table 3).
- Temperature showed strong evidence of seasonality (Table 5).
- Surface nutrient concentrations were highly correlated with bottom nutrient concentrations (Table 6).
- Data censoring rates were high for $\text{NO}^{-3} + \text{NO}^{-2}$ (at Tutuila), TDP, chlorophyll (at Ofu), and turbidity (Appendix E).
- No SGD plumes were detected.
- No spatial patterns were detected.

Discussion

Overall water quality in the marine portions of PACN parks was good, with low nutrient concentrations, predominance of dissolved nutrient species, high oxygenation, high clarity, and thus oligotrophic. Nutrient concentrations were generally consistent with previous studies (Table 9). Note that because the sampling regime differed from methods employed by state agencies, results of the current study were not directly comparable to state water quality standards. Water quality parameter values representing outliers were uncommon and attributable to identifiable non-repeating causes such as a possible minor algal bloom in Kaloko-Honokōhau NHP in 2010. The Honokohau small boat harbor plume was the only area with high nutrient concentration conditions that were of concern. Some data in some parks showed a low proportion of dissolved nutrients, which were likely caused by particulates suspended by wave action disturbing the bed or surface water discharge, especially at War in the Pacific NHP. Suspension of benthic nutrients into the water column at War in the Pacific NHP may explain temporal patterns that were more temporally stochastic than other parks, and lower correlations observed between surface and near-bottom samples. With the exception of TDN, water quality parameter values and temporal patterns were unremarkable. Kalaupapa NHP experienced a precipitous drop in TDN concentrations in 2014 (Figure 9). At this time the drop in TDN is unexplained. However, TDN concentrations at Kalaupapa were very low for the entire monitoring period, always below the range typically found in nearshore environments of Hawaii (Table 9), and the absolute value of the drop was not likely to have been ecologically significant given such low concentrations in this area.

Table 9. Nutrient concentration means or ranges in groundwater, directly measured submarine groundwater discharge (SGD), SGD plumes, and/or ambient Pacific island nearshore seawater.

Nutrient Species	Ground-water (µg/L) ^a	SGD (µg/L) ^a	SGD Plume (µg/L) ^a	Seawater (µg/L) ^a	Location	Reference
SRP	–	–	–	7 ^h	Tumon Bay, Guam	Porter et al. 2005
	53 – 681	–	–	16 – 26	Moorea, French Polynesia	Knee et al. 2016
	39 – 120 ^b	–	–	2 – 11	Maui	Amato, et al. 2016
	31 – 152 ^c	–	–	7 – 13	Maui	Amato, et al. 2016
	77 ^d	–	–	3	Puakō Hawai'i ^e	Abaya et al. 2018
	8 – 11 ^f	–	–	3 – 4 ^f	Kaua'i	Knee et al. 2008
	–	–	–	2.8 – 39	Kailua Bay, Hawai'i	Johnson et al. 2008
	–	–	–	2.8 – 118	Kealakekua Bay, Hawai'i	Johnson et al. 2008
	–	–	–	3.1 – 209	Honokohau Harbor, Hawai'i	Johnson et al. 2008
	–	–	26	6	Kona coast, Hawai'i	Street et al. 2008
	–	–	22	3	Kailua, Hawai'i ^e	Carlson & Wiegner 2016
NO ₃ [–] + NO ₂ [–]	118 – 136	–	9 – 108	6 – 12	Kaloko-Honokohau NHP ^g	Knee et al. 2010
	–	–	–	40 ^h	Tumon Bay, Guam	Porter et al. 2005
	35 – 109	–	–	2 – 6	Moorea, French Polynesia	Knee et al. 2016
	1841 ^d	–	–	20	Puakō, Hawai'i ^e	Abaya et al. 2018
	188 – 360 ^f	–	–	18 – 23 ^f	Kaua'i	Knee et al. 2008
	–	–	238	77	Kailua, Hawai'i ^e	Carlson & Wiegner 2016
	–	–	37	14	Kaloko-Honokohau NHP	Johnson Wiegner 2013

^a = Conversion from micromoles to grams assuming reported values are as N or P.

^b = “Low-N” sites.

^c = “High-N” sites impacted by sewage.

^d = Low elevation wells.

^e = Leeward west coast of the Island of Hawai'i.

^f = Inferred.

^g = All sites within the park.

^h = Rainy season.

ND = Non-detect.

Table 9 (continued). Nutrient concentration means or ranges in groundwater, directly measured submarine groundwater discharge (SGD), SGD plumes, and/or ambient Pacific island nearshore seawater.

Nutrient Species	Ground-water (µg/L) ^a	SGD (µg/L) ^a	SGD Plume (µg/L) ^a	Seawater (µg/L) ^a	Location	Reference
NO ₃ ⁻ + NO ₂ ⁻	924 – 1163	–	20 – 406	20 – 84	Kaloko-Honokohau NHP ^g	Knee et al. 2010
	17 – 1891	–	–	39 – 48	Moorea, French Polynesia	Knee et al. 2016
NH ₄	–	–	ND	ND	Kailua, Hawai'i ^e	Carlson & Wiegner 2016
	68 ^d	–	–	35	Puakō, Hawai'i ^e	Abaya et al. 2018
	14 – 54 ^f	–	–	10 – 13 ^f	Kaua'i	Knee et al. 2008
	3 – 7	–	6 – 14	6 – 18	Kaloko-Honokohau NHP ^g	Knee et al. 2010
	185	224	–	116	Inner Kahana Bay, O'ahu	Garrison et al. 2003
TDN	81 – 318 ^b	–	–	55 – 112 ^b	Maui	Amato, et al. 2016
	759 – 7336 ^c	–	–	157 – 419 ^c	Maui	Amato, et al. 2016
	–	–	294	182	Kailua, Hawai'i ^e	Carlson & Wiegner 2016
	124	23	–	12	Inner Kahana Bay, O'ahu	Garrison et al. 2003
TDP	37 – 106 ^b	–	–	0 – 3 ^b	Maui	Amato, et al. 2016
	28 – 163 ^c	–	–	5 ^c	Maui	Amato, et al. 2016
	–	–	22	12	Kailua, Hawai'i ^e	Carlson & Wiegner 2016

^a = Conversion from micromoles to grams assuming reported values are as N or P.

^b = “Low-N” sites.

^c = “High-N” sites impacted by sewage.

^d = Low elevation wells.

^e = Leeward west coast of the Island of Hawai'i.

^f = Inferred.

^g = All sites within the park.

^h = Rainy season.

ND = Non-detect.

General non-detection of TDP at nearly all PACN parks was not surprising given that dissolved phosphorus is highly labile and ecologically important to plankton. Concentrations of TDN matched ranges found in “low-N” sites not impacted by sewage on Maui (Amato et al. 2016), were consistent with Inner Kahana Bay on Oahu (Garrison et al. 2003) and were slightly less than seawater measurements at Kailua-Kona along the Kona coast of the Island of Hawai‘i (Carlson and Wiegner 2016). TDN and $\text{NO}_3^- + \text{NO}_2^-$ concentrations were greater at the surface in areas near and south of the Honokohau Small Boat Harbor mouth indicating that SGD plumes were directly sampled (Table 9, Figures 7 and 8).

Measurements from sites near the mouth of Honokohau Small Boat Harbor also demonstrated that tides can greatly affect water quality parameters values in the nearshore marine environment of Kaloko-Honokōhau NHP. The tide appeared to influence TDP at the surface (Figure 14), TDN at the surface and bottom, $\text{NO}_3^- + \text{NO}_2^-$ at the surface and bottom, and temperature at the surface (see also Raikow, Farahi, Kichman, and McCutcheon 2017). During many ebb tides water near the mouth of the harbor was cooler, more nutrient rich, and less saline; while during many flood tides values were more evenly distributed across the study area (Figures 15 and 16). These patterns were consistent with the known SGD plume released by the Honokohau Small Boat Harbor (Bienfang 1980). Discrepancies in this relationship within the dataset may have been the result of varying tidal intensities, precipitation, and the precise time that samples were taken at an individual station across the sequence of a sampling event.

At War in the Pacific NHP Asan unit, observed salinities and temperatures were comparable to those observed by Storlazzi et al. (2009) at their deeper sites, including the lowest temperatures and salinities observed in the present study. Observed salinities and temperatures at Agat were also comparable to those observed by Storlazzi et al. (2014). Lower concentrations of $\text{NO}_3^- + \text{NO}_2^-$, greater oxygen saturation, and similar pH, salinity, and turbidity were observed at both Asan and Agat compared to Tumon Bay (Porter et al. 2005). These results could be explained by much less extensive urban development and human use at Asan and Agat compared to Tumon Bay, which is the center of tourism in Guam.

Submarine groundwater discharge and surface runoff

Submarine groundwater discharge is known to supply land-derived materials to nearshore environments including nutrients (Li et al. 1999, Slomp et al. 2004, Fabricus 2005, Paytan et al. 2006, Knee et al. 2016), fecal indicator bacteria (Knee et al. 2008, Abaya et al. 2018), and pollutants including metals, pesticides, and emerging contaminants (Knee and Paytan 2011). Nutrient loads supplied to marine nearshore environments by SGD can equal or exceed inputs supplied by surface runoff (Moore 1999, Garrison et al. 2003, Knee et al. 2008). Discharge of groundwater into nearshore marine environments can be ever present, but discharge amounts can vary over time (Holliday et al. 2007, Dulai et al. 2016). While SGD may be volumetrically dominated by recirculated seawater, accounting for over 90% of the total volume of water moving into the ocean at any one time, terrestrially derived groundwater delivers nutrient subsidies to nearshore marine environments (Li et al. 1999). Land-use and landscape features are known to directly affect the nutrient composition of SGD (Knee et al. 2010), including harbors (Bienfang 1980), golf courses (Dollar and

Atkinson 1992, Wong et al. 1998, Knee et al. 2010), terrestrial agriculture (Amato et al. 2016), and wastewater treatment plants (Amato et al. 2016). Increased nutrient concentrations derived from anthropogenic disturbance found in nearshore marine environments has been linked to changes to benthic community structure (McCook 1999), eutrophication (Gonzalez et al. 2008), and harmful algal blooms (Paerl et al. 2018).

On volcanic islands, SGD flux (flow or delivery rate per unit area or distance) can be very large compared to continental shorelines (Burnett et al. 2006). Individual nutrient concentrations carried by groundwater and SGD can greatly exceed that of seawater (Table 3). For example, high water flux and nutrient concentrations result in large nutrient loads (total mass) delivered to the nearshore marine environments of Oahu and Kaua'i (Garrison et al. 2003, Knee et al. 2008), and marine algae at the Maui shoreline take up terrestrially-derived SGD-delivered nutrients (Dailer et al. 2010). Reciprocal aquifer-open water exchange also makes evaluation of near-shore marine water quality pertinent to terrestrial coastal aquatic ecosystems. Consideration of marine influence on terrestrial coastal aquatic ecosystems is of particular importance to Kaloko-Honokōhau NHP due to a large and dense population of anchialine pools, a globally rare waterbody type. The historically dominant interest of researchers and resource managers, however, has been the effect of SGD-supplied materials to marine ecosystems such as corals reefs.

Kona Coast hydrology, both inland and offshore, has been the subject of much interest by competing stakeholders primarily with regard to development, seawater infiltration of aquifers, and nutrient enrichment (Duarte 2010, Brauman et al. 2014). Increased upslope human settlement may result in nutrient-enriched groundwater that could affect both anchialine pools and nearshore marine aquatic ecosystems. Upslope extraction of freshwater and/or sea-level rise could result in increased seawater infiltration of the terrestrial aquifer, affecting anchialine pools and residential water sources. Due to such interests, the lack of surface runoff at Kaloko-Honokōhau NHP, and steep topography the Kona coast of the Island of Hawai'i has been a focus of SGD research (Street et al. 2008).

Imagery and water quality observations along the Kona Coast have clearly shown highly localized spatial patterns of water quality parameters including nutrients caused by SGD. The locations of large individual point-source SGD plumes have been identified extending up to 100–200m offshore (e.g. Johnson et al. 2008, Carlson and Wiegner 2016). Marine nutrient concentrations range widely along the coastline, e.g. while Johnson et al. (2008) measured low soluble reactive phosphorus (SRP, $\leq 10 \mu\text{g/L}$) at ~75% of sites, values ranged as high as $209 \mu\text{g/L}$ in Honokohau Harbor (Table 3). Submarine groundwater discharge plumes on the leeward side of the Island of Hawai'i have been directly sampled and found to have higher concentrations of SRP, TDP, TDN, and $\text{NO}_3^- + \text{NO}_2^-$ than ambient seawater (Table 3; Carlson and Wiegner 2016). Localized variation of water quality parameters has also been observed on other Pacific islands (Knee et al. 2008, Knee et al. 2016). While flow rates of individual SGD plumes (e.g. Bienfang 1980; Peterson et al. 2009) and flux rates (reviewed by Street et al. 2008) have been estimated, SGD varies spatially and temporally, including along the Kona Coast. Naturally occurring radium (a tracer of fresh groundwater) activity along the Kona coast was inversely correlated with tide stage, demonstrating decreased fresh groundwater input to nearshore environments during high tide (Peterson et al. 2009). Modeled SGD flux

decreased during the period of rising water reaching high tide and increased during the period of falling water following high tide (Peterson et. al. 2009).

Sources of SGD observed in Kaloko-Honokōhau NHP include point sources at a location near the north border of the park and golf course, the ‘Aimakapā Fishpond, Honokōhau Harbor, and areas of diffuse flow including the shoreline along Kaloko Fishpond and ‘Ai‘ōpio Fishtrap (Johnson et al. 2008). Lower salinity has been measured up to 1 km offshore from Honokōhau Harbor (Knee et al. 2010). SGD flux at Honokōhau beach was up to three times higher at low tide (0.39 to 0.65 m³/m²/d) than at high tide (0.10 to 0.23 m³/m²/d); and SRP and dissolved inorganic nitrogen (DIN) concentrations greater during ebb tide than flood tide (Street et al. 2008). Greater chlorophyll concentrations, phytoplankton biovolumes, gross primary production and respiration than ambient seawater have been observed within SGD plumes in Kaloko-Honokōhau NHP (Johnson and Wiegner 2014). Nearshore water at multiple locations within Kaloko-Honokōhau NHP have been observed to be much less saline than the open ocean and with higher concentrations of nutrients such as SRP, NO⁻₃ + NO⁻₂, and ammonium (NH₄; Knee et al. 2010).

Submarine groundwater discharge may have contributed to the possible algal bloom at Kaloko-Honokōhau NHP in 2010 in response to increased terrestrial rainfall following a shift to La Niña conditions. A single algal bloom might be expected to display increased chlorophyll, pH, turbidity, and oxygen concurrently. The staggered observations of conditions between late 2010 and early 2011 suggest that conditions may have existed during this time to allow multiple minor blooms, as currents in the area might be expected to flush a single bloom out of the area in a relatively short time. Further, while chlorophyll generally increases with algal abundance this relationship has considerable variance due to varying concentrations of chlorophyll among algal species making chlorophyll alone insufficient to evaluate the presence of an algal bloom. The unusual conditions observed during this time were likely caused by unusually heavy rains causing a high influx of terrestrially derived nutrients and material after a period of drought conditions (Figure 18).

Higher nutrient concentrations relative to other sample sites within sampling events were regularly observed at the surface near the mouth of Honokohau Harbor. Concentrations of TDN and NO⁻₃ + NO⁻₂ were greater at the surface near and to the south of the Honokohau Small Boat Harbor mouth clearly indicating sampling of an SGD plume (Figures 7 and 8). Nutrient-enriched plumes exiting Honokohau Small Boat Harbor were consistent with observations that the coral community in the vicinity of the harbor mouth is abundant in octocorals that may be indicators of pollution (Walsh et al. 2009). Measurements from sites near the mouth of Honokohau Small Boat Harbor further demonstrated that tides can greatly affect water quality parameters values in the nearshore marine environment of Kaloko-Honokōhau NHP. Other observations were consistent with SGD at Kaloko-Honokōhau NHP, whereby water near the bottom displayed lower concentrations of nutrients, chlorophyll, and dissolved oxygen. Thus, SGD was directly observed at Kaloko-Honokōhau NHP, consistent with previous studies and upland nutrient inputs derived from the movement of meteoric precipitation through the aquifer and introduced to nearshore marine environments. No evidence of SGD was observed at other parks.

Notably, the marine nearshore environment of War in the Pacific NHP are influenced heavily by surface runoff and not influenced by SGD. Asan Beach and inland park units encompass most of Asan Bay and much of the Asan River and its watershed; and the Agat Unit encompasses much of Agat Bay and part of its watershed. Terrestrial inputs to Asan and Agat Bays are dominated by surface water discharges (Storlazzi et al. 2009, Storlazzi et al. 2014). Bars can form at the Asan River mouth restricting flow into the bay and washing out during high discharge or high ocean wave events (Storlazzi et al. 2009). The Asan River releases fine particulates during discharge events leading to high sedimentation rates (Minton et al. 2007). Shallow near-shore areas can warm during the day but temperature and salinity there are not greatly affected by tide conditions, high wind, or waves; while deeper areas offshore show decreasing temperatures and increasing salinity with tides (Storlazzi et al. 2009). An Asan River discharge event observed by Storlazzi et al. (2009) increased turbidity from close to 0 NTU to over 100 NTU in nearshore areas and created a plume that peaked approximately 3.5 hours later and subsided approximately 7.0 hours later at sites further offshore at the 20m depth isobar. Surface runoff affected particulate nutrient fractions. The distribution of dissolved nutrient fractions included far-left outliers at War in the Pacific NHP compared to other parks. Instances of high proportions of particulates (seen as low values in Figure 21) indicate particulates flushed into the nearshore marine environment from rivers and streams. Surface runoff also likely affected some nutrient measurements, e.g. the very high outlying 0.44 mg/L TDN observation at Agat (Figure 7) was at a site located 450 m from the mouth of the Namo River. There was no evidence of surface runoff events at KALA, KAHO, or NPSA.

Climate and Temporal Patterns

Climate change is a long-term factor with the potential to affect water quality, especially physiochemical factors like pH, temperature, and salinity. Varying in extent globally, sea surface pH has fallen by ~0.5 as a direct result of increased atmospheric CO₂ concentration and carbonic acid equilibrium (EPA 2016). Marine surface water temperature has risen ~0.5°C since 1980 (EPA 2016). Climate change effects on salinity are indirect. Marine salinity in an area, or the “salinity field,” is driven by evaporation, precipitation, river discharge, SGD, and the effect of wind on water circulation, all of which are integral and interacting components of climatological processes (Knee and Paytan 2011; Yu 2011; Durack et al. 2012; Pierce et al. 2012). The relative importance of salinity field drivers varies globally, with rainfall-dominated regions displaying lower salinities (Yu 2011; Durack et al. 2012). Salinity is directly coupled with temperature in marine systems by evaporation, and in the case of Pacific islands, local updraft of moisture-laden water and subsequent precipitation (Oki 1999). Because patterns in the salinity field are easy to measure compared to quantifying change in local water cycles, spatial and temporal patterns in the marine salinity field have been proposed as sentinel indicators of climate change (Durack et al. 2012; Pierce et al. 2012).

There is evidence to suggest climate change may be affecting oceanic currents on a broad-scale in the North Atlantic and Antarctic regions, but global-scale patterns are not well understood (Bindoff et al. 2007). However, some predictions have been made with respect to the near-shore environments of Pacific islands that may affect some aspects of ocean currents (Storlazzi 2015). Generally, wave-models using wind-fields generated from global climate-models predict increased wave action on northern shores and decreased wave action on southern shores. Thus, it can be inferred that the

mixing effect of wind-driven waves may deepen along north shores and lessen along southern shores. Change in the directions of major currents around Pacific islands has not been predicted. Thus, because the marine portions of Pacific island parks reside entirely within the mixed surficial oceanic layer, sources of marine-derived nutrients found in monitored waters are not expected to change.

Generalizations for ENSO effects on regions in the Pacific Ocean are made over large spatial scales encompassing open waters. As such, deviations from general regional patterns are possible within nearshore environments due to SGD, currents, and unique local conditions, especially with regard to mountains near shorelines creating rain shadows and/or local land-sea precipitation cells (John Marra, NOAA, personal communication). Therefore, while consideration of ENSO effects is important, deviation from general regional patterns should not be surprising. Further, because there are other ways of calculating a numerical representation of ENSO, and because the timing of climatological effects occurs earlier in the western Pacific, the Oceanic Niño Index should be interpreted as a general temporal description of ENSO phase transitions.

Less terrestrial rainfall at Kaloko-Honokōhau meant there was less freshwater available in groundwater supplied to the shore during the early part of the monitoring period, followed by greatly increased contributions in the latter part of the monitoring period. The wide range of precipitation over a relatively short time period afforded an opportunity to observe how the coastal nearshore environment responded to extremes of terrestrial precipitation. Salinity was high relative to the monitored period in 2009, and relatively low in 2011 and 2015 during high rainfall (Figure 11). Therefore, while a decreasing trend in salinity was detected at Kaloko-Honokōhau NHP from 2008–2015 (Figure 13), this pattern likely reflected the timing of ENSO-induced changes in precipitation, and therefore cannot be reliably identified as a detrimental long-term trend at this time. Overall, the time period reported is as yet too short to evaluate long-term trends in salinity given the magnitude of variation caused by ENSO effects with multi-year durations. The Kaloko-Honokōhau NHP rainfall correlation results suggested that nearshore salinity responded to precipitation that had fallen during two time periods: precipitation falling within a month of the measurement and presumably close to shore, and precipitation that had taken three to four months to travel downslope. Such differential groundwater travel times could also be caused by varying underlying geologic conditions.

The trend of an increase in temperature observed at Kaloko-Honokōhau NHP over the monitoring period may have been an artifact of variation. The lowest temperatures were observed at the beginning of the monitored period, and the highest at the end (Figure 13). If these temperatures represent extremes of the normal range, then these data applied leverage to the overall curve defining the trend. Alternatively, the trend in temperature may have been an effect of ENSO, as sea surface temperatures in the Pacific generally drop at the beginning of an El Niño, then rise to higher than average afterward (Rupic et al. 2018). These results, however, should not be used to argue there is an absence of temperature increase in the marine waters of NPS units of the Pacific, as it was simply just too short of a time period to demonstrate such changes. Observed temperatures were generally consistent with long-term monitoring of near-shore ocean temperatures (NOAA 2017).

Kalaupapa NHP is located on the north side of Molokaʻi, intersects trade winds directly, and receives heavy rainfall. Despite more direct potential interaction with weather patterns affected by ENSO, the

response of the marine nearshore environment of Kalaupapa NHP to ENSO was less apparent than that for Kaloko-Honokōhau NHP. There was no ENSO-driven explanation for the low salinity observation in 2015 and may represent an uncommon but normal variation in local conditions. The timing of the high and low salinity readings had leverage with respect to the curve defining the trend. Therefore, the observed decrease in salinity can be partially explained by ENSO and cannot be identified as a trend warranting concern. Similarly, the observed increasing trend in temperature can also be partially explained by ENSO, as the lowest temperature was recorded when the El Niño phase was at its peak (Figures 18 and 20).

At War in the Pacific National Historical Park, ENSO effects on temporal rainfall patterns were relatively minor compared to Hawaii's response to ENSO over the same period (Figure 21). A drop in marine temperature and salinity was observed subsequent to high rainfall at both Asan and Agat in 2010 (Figures 10 and 11) and may be attributed to surface freshwater runoff. Another reduction in salinity, but without a corresponding drop in temperature, was observed in 2014 (Figure 10 and 11). There was no exceptionally high rain during this time comparable to 2010. However, 0.9 in. (2.3 cm) of rain fell in one day a few days before sampling was initiated, while the previous three weeks saw an average of 0.15 in (0.40 cm, range of 0.0 to 0.51 in., 0.0 to 1.3 cm.). Therefore, it is possible that the low salinity observed in 2014 was an effect of very recent rainfall. While the nearshore marine areas of Guam appear to be affected by terrestrial rainfall, the response occurs more quickly and lasts for a shorter amount of time than the response observed at Kaloko Honokōhau NHP. At Kaloko Honokōhau NHP there is no surface flow while SGD is very prominent, but the opposite is true for War in the Pacific NHP. SGD may diffuse the effects of rainfall, both high and low, over time on marine nearshore environments while the effect of surface flows is highly reactive by comparison (Storlazzi et al. 2009). In any case, trends in salinity at War in the Pacific NHP during this study are likely the result of runoff, perhaps in turn affected by ENSO, rather than representing a detrimental long-term trend.

The decrease in chlorophyll at Agat was also likely not a detrimental long-term trend but an artifact of the timing of runoff events. At both Asan and Agat a spike in chlorophyll was observed in early 2010. The timing of this spike near the beginning of the monitoring period, and thus this datum had high leverage. This spike corresponds to the very high rainfall that appears to have affected salinity. It is possible that a pulse of nutrients was delivered to the nearshore environment, stimulating phytoplankton. However, TDN, TDP, and $\text{NO}_3^- + \text{NO}_2^-$ did not show a corresponding increase. Compared to other parks, Agat and Asan have substantial human settlements combined with significant surface runoff.

Unlike other PACN locations, American Samoa is further influenced by the Southern Pacific Convergence Zone (SPCZ), a band of convergence, cloud cover and precipitation extending from the equator south west across the southern Pacific (Vincent 1994). The SPCZ is affected by the ENSO cycle and the Interdecadal Pacific Oscillation (IPO) by being shifted north or south (Folland et al. 2002). Due to American Samoa's location, small changes in the north-south orientation of the SPCZ can alter annual rainfall patterns. Generalizations on the effect of ENSO and IPO on the SPCZ are difficult for small specific locations such as American Samoa, making direct examination of rainfall

more useful. National Park of American Samoa displayed a climatological response that differed from other parks. Moreover, because there was no weather station of the Island of Ofu, it is not known if precipitation patterns differed from those at Tutuila during the monitoring period. Hence, there is no evidence that precipitation was responsible for the observed decrease in salinity. It is unclear whether the detected trend is the result of long-term changes or the timing of climatological events as in other parks. At this time the decline in salinity is biologically trivial and may represent natural variability.

Implications for Monitoring Protocol Design

One major difficulty in choosing an optimal sampling design for a new monitoring program is a lack of prior knowledge (Skalski 1990). While exhaustive a priori review of what is known about the ecosystems and areas to be monitored is required to optimize monitoring program design, examination of monitoring data may reveal a need to modify design (Oakley et al. 2003). Hence, a long-term iterative cycle of monitoring, analysis, and adjustment can be established to optimize the detection of harmful trends and unexpected conditions (Lindenmayer et al. 2010). The NPS IMD program recognized this potential and incorporated empirically based modification of the sampling regime following examination of trends into the objectives and standard operating procedures of its protocols (e.g. Jones et al. 2011). Analysis of data from the first seven years of this monitoring program clearly showed where methodology of the monitoring program can be improved. Provide a specific and detailed summation of the conclusions of the study. In some instances, this is one of the few parts of the report that park managers will read. If the research was initiated due to specific park management needs, management implications should be emphasized and thoroughly discussed.

“Near-bottom” sampling should be eliminated because it did not increase general ecological understanding of park ecosystems, was redundant to surface sampling, added monetary cost, and did not actually target benthic processes. Lack of insight was due to near-bottom samples being highly correlated with surface samples and thus not showing different temporal patterns (Table 6). While co-locating water quality sampling sites can support monitoring conditions that corals and other benthic invertebrates are subject to, below-surface sampling as conducted was simply not deep enough; i.e. water sampled 2–3 m above the bottom is already within the water column mixed by wind-driven wave action and thus it should not be surprising that these mid-column samples were highly correlated with the surface. Moreover, climate-change induced alteration of wind-induced mixing will not be detected by the current “near-bottom” sampling methods because these samples are already in the mixed layer. Thus, to directly monitor benthic water quality samples must be taken directly at the seabed, i.e. within centimeters, not meters. We recommend sampling water at the bottom by SCUBA divers to assess feasibility of detecting potential differences in water quality between the surface and conditions experienced by benthic organisms.

Differences that were observed in some parameters between surface and near-bottom samples were due to unremarkable and well-understood phenomena, such as wave action oxygenating surface waters, light at the surface stimulating algae that consume nutrients and produce chlorophyll, and previously known SGD plumes (e.g. Bienfang 1980). Other mechanisms affecting nutrient abundances are either detectable in surface samples, such as resuspension of benthic nutrients, or better studied at the surface, such as SGD. Hence given the importance of processes that dominate surface water dynamics, such as SGD and surface runoff from populated areas surrounding park lands, surface waters should be the focus of the PACN water quality program. Eliminating near-bottom samples would have no effect on future data quality or the ability to detect trends.

Temporary sites should be eliminated because they did not differ from fixed sites and can be randomly placed within demonstrably different plumes. Revisitation-designs, such as the fixed and

temporary site panels used here, have advantages but depend on sample sites being representative of the area sampled (Urquhart et al 1998). The placement of sample sites in the present study did not take landscape-features into account, and therefore did not represent study areas, introducing a confounding factor. The data showed that spatial variation can exist in the marine water quality of Pacific parks (Figures 14 and 15). The spatial variation observed at Kaloko-Honokōhau was caused by an SGD plume emanating from the Honokohau Small Boat Harbor (Beinfang 1980). Differences in nutrients between the SGD plume and other waters were clear when data within the plume were separated from data collected elsewhere (Figure 6). Because conditions differed fundamentally at the mouth of the Honokohau harbor compared to the rest of the Kaloko-Honokōhau marine area, site FKAHO12_mr and any temporary sites randomly assigned to the plume should be analyzed as a group separate from other sites in future analyses. In addition, the potential spatial influence of the Asan River at WAPA, and streams at other parks is not known, and therefore should be examined.

Data collected at fixed sites did not differ from data collected at temporary sites statistically, biologically, or temporally in substantial ways (Table 7, Appendix G). While the addition of temporary sites to a panel-based revisit design can improve trend detection in spatially large or heterogeneous sample populations (Starceovich et al. 2018), data from temporary sites did not improve detection of trends in the present study. Such results show that the small marine areas monitored by PACN are largely homogenous but for highly localized, condition-altering, spatially predictable phenomena such as the harbor plume and possibly other plumes close to shore caused by SGD and rivers. Because of the small size of the areas monitored, adding fixed sites and removing temporary sites will not result in loss of insight to the area, but will improve the ability to detect change. Currently, temporary sites can be placed in plumes that would confound the intended randomized design. Eliminating temporary sites would avoid such confounding factors and allow focused evaluation of known and potential SGD and surface water inputs. Improved long-term monitoring and understanding of park ecosystems requires evaluating demonstrated spatial patterns representing spatial heterogeneity. Continuing to monitor previously established fixed sites avoids confounding spatial factors without interruption of the long-term dataset (Fancy et al. 2009).

Shifting to a design that distributes sample sites in order to reflect spatial heterogeneity is consistent with both general recommendations for marine water quality monitoring program design, specifically with regard to shore-based pollution sources (Karydis and Kitsiou 2013), and recommendations made by NPS in its original guidelines for monitoring program design. For example, Irwin (2004) explicitly states: 1) “plans will include justifications for factors used to stratify parks into sample units...e.g. terrain features,” 2) “the plan should describe what is known about average values and variability in various strata,” and 3) “the plan shall detail how the sampling scheme will insure that the value obtained will be representative of the target population being studied.” Fancy et al. (2009) states: “It is legitimate, and better, to delineate areas of special interest...based on physical characteristics...and to use these to judiciously define... strata.” Moreover, including SGD and surface water plumes in the consideration of sampling design is consistent with accounting for ecological processes that affect park resources (Fancy et al. 2009).

Other improvements can be made regarding temporal variation in marine water quality. The sampling design did not account for tide, but results demonstrated its importance. The influence of SGD and its variability during different tidal stages was visible at Kaloko-Honokōhau NHP, and runoff was likely important at War in the Pacific NHP. Because SGD and runoff are such important mechanisms for the delivery of materials to nearshore marine environments, understanding impacts from terrestrial areas in and around parks can be optimized by sampling during ebb tides. The timing of rain events that could produce surface water plumes should be recorded and accounted for in future sampling, especially at War in the Pacific NHP where no weather station currently exists. Sampling river discharge in cooperation with other agencies that routinely do such work would provide critical insights to evaluate long term trends in ambient conditions of the entire study area.

Summary of Recommendations

- Eliminate near-bottom sampling.
- Eliminate temporary sites and retain fixed sites.
- Add new fixed sample sites to improve spatial coverage and monitor SGD and river discharge.
- Sample during ebb tide.
- Sample river discharge events.

Literature Cited

- Abaya, L. M., T. N. Wiegner, S. L. Colbert, J. P. Beets, M. C. Kaile'a, K. L. Kramer, R. Most, and C. S. Couch. 2018. A multi-indicator approach for identifying shoreline sewage pollution hotspots adjacent to coral reefs. *Marine Pollution Bulletin* 129(1):70–80.
- Amato, D. W., J. M Bishop, C. R. Glenn, H. Dulai, and C. M. Smith. 2016. Impact of submarine groundwater discharge on marine water quality and reef biota of Maui. *PloS one* 11(11) p.e0165825.
- Bates, D. M. 2010. lme4: Mixed-effects modeling with R.
- Bates D., M. Machler, B. M. Bolker, and S. C. Walker. 2014. Fixed linear mixed-effects models using lme4. *Journal of Statistical Software* 67(1): 1–48.
- Bienfang, P. 1980. Water quality characteristics of Honokohau Harbor: A subtropical embayment affected by groundwater intrusion. *Pacific Science* 34:279–291.
- Birkeland, C., P. Craig, D. Fenner, L. W. Smith, W. E. Kiene, B. Riegl. 2007. Geologic setting and ecological functioning of coral reefs in American Samoa. Chap. 20. 10.1007/978-1-4020-6847-8_20.
- Bindoff, N. L., J. Willebrand, V. Artale, A. Cazenave, J. Gregory, S. Gulev, K. Hanawa, C. Le Quéré, S. Levitus, Y. Nojiri, C.K. Shum, L.D. Talley and A. Unnikrishnan. 2007. Observations: Oceanic Climate Change and Sea Level. Pages 387–431 in S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller, editors. *Climate Change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change* Cambridge University Press, Cambridge, United Kingdom and New York, New York.
- Brauman, K. A., D. L. Freyberg, and G. C. Daily. 2014. Impacts of land-use change on groundwater supply: Ecosystem services assessment in Kona, Hawaii. *Journal of Water Resources Planning and Management* 141(12): p.A4014001.
- Burnett, W. C., P. K. Aggarwal, A. Aureli, H. Bokuniewicz, J. E. Cable, M. A. Charette, E. Kontar, S. Krupa, K. M. Kulkarni, A. Loveless, and W. S. Moore. 2006. Quantifying submarine groundwater discharge in the coastal zone via multiple methods. *Science of the total Environment* 367(2–3):498–543.
- Burnett, W.C., H. Bokuniewicz, M. Huettel, W. S. Moore. and M. Taniguchi. 2003. Groundwater and pore water inputs to the coastal zone. *Biogeochemistry* 66(1–2):3–33.
- Carlson, K. M. and T. N. Wiegner, 2016. Effects of submarine groundwater discharge on bacterial growth efficiency in coastal Hawaiian waters. *Aquatic Microbial Ecology* 77(3):167–181.

- Camargo, J. A., and Á. Alonso. 2006. Ecological and toxicological effects of inorganic nitrogen pollution in aquatic ecosystems: A global assessment. *Environment International* 32(6): 831–849.
- Dailer, M. L., R. S. Knox, J. E. Smith, M. Napier, and C. M. Smith. 2010. Using $\delta^{15}\text{N}$ values in algal tissue to map locations and potential sources of anthropogenic nutrient inputs on the island of Maui, Hawai‘i, USA. *Marine Pollution Bulletin* 60(5):655–671.
- Dollar, S., and M. J. Atkinson. 1992. Effects of nutrient subsidies from groundwater to nearshore marine ecosystems off the island of Hawaii, *Estuarine Coastal and Shelf Science* 35(4):409–424.
- Duarte, T. K., S. Pongkijvorasin, J. Roumasset, D. Amato, and K. Burnett. 2010. Optimal management of a Hawaiian Coastal aquifer with nearshore marine ecological interactions. *Water Resources Research* 46(11).
- Dulai, H., J. Kamenik, C. A. Waters, J. Kennedy, J. Babinec, J. Jolly, and M. Williamson. 2016. Autonomous long-term gamma-spectrometric monitoring of submarine groundwater discharge trends in Hawaii. *Journal of Radioanalytical and Nuclear Chemistry* 307(3):1865–1870.
- Durack, P. J., S. E. Wijffels, and R. J. Matear, 2012. Ocean salinities reveal strong global water cycle intensification during 1950 to 2000. *Science* 336:445–458.
- EPA (U.S. Environmental Protection Agency). 2016. Climate change indicators in the United States, 2016. Fourth edition. EPA 430-R-16-004. www.epa.gov/climate-indicators.
- Fabricius, K. E. 2005. Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. *Marine Pollution Bulletin* 50(2): 125–146.
- 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* 151:161–174.
- Folland, C. K., J. A. Renwick, M. J. Salinger, and A. B. Mullan. 2002. Relative influences of the interdecadal Pacific oscillation and ENSO on the South Pacific convergence zone. *Geophysical Research Letters* 29(13):21-1–21-4.
- Garrison, G. H., C. R. Glenn, and G. M. McMurtry. 2003. Measurement of submarine groundwater discharge in Kahana Bay, O‘ahu, Hawai‘i. *Limnology and Oceanography* 48(2):920–928.
- Gilbert, P. M. 2012. Ecological stoichiometry and its implications for aquatic ecosystem sustainability. *Current Opinion in Environmental Sustainability* 4(3):272–277.
- Gonzalez, F. U. T., J. A. Herrera-Silveira, M. L. Aguirre-Macedo. 2008. Water quality variability and eutrophic trends in karstic tropical coastal lagoons of the Yucatán Peninsula. *Estuarine, Coastal and Shelf Science* 76:418–430.
- HaySmith, L., F. L. Klasner, S. H. Stephens, and G. H. Dicus. 2005. Pacific Island Network Vital Signs monitoring plan. Natural Resource Report NPS/PACN/NRR—2006/003. National Park Service, Fort Collins, Colorado.

- Helsel, D. R. and Hirsch, R. M. 2002. Statistical methods in water resources (Vol. 323). Reston, VA: US Geological Survey.
- Holliday, D. T., C. Stieglitz, P. V. Ridd, and W. W. Read. 2007. Geological controls and tidal forcing of submarine groundwater discharge from a confined aquifer in a coastal sand dune system. *Journal of Geophysical Research* 112:C04015. doi.org/10.1029/2006JC003580.
- Irwin, R. J. 2004. Draft part B of aquatic habitat park service guidance for park service guidance for park service vital signs monitoring, Water Resources Division, National Park Service.
- Johnson, A. G., C. R. Glenn, W. C. Burnett, R. N. Peterson, P. G. Lucey. 2008. Aerial infrared imaging reveals large nutrient-rich groundwater inputs to the ocean, *Geophysical Research Letters* 35 L15606. doi.10.1029/2008GL034574.
- Johnson, E. E., and T. N. Wiegner. 2014. Surface water metabolism potential in groundwater-fed coastal waters of Hawaii Island, USA. *Estuaries and Coasts* 37(3):712–723.
- Jones, T., K. DeVerse, G. Dicus, D. McKay, A. Farahi, K. Kozar, and E. Brown. 2011. Water quality vital signs monitoring protocol for the Pacific Island Network: Volume 1; Version 1.01. Natural Resource Report NPS/PACN/NRR—2011/418. National Park Service, Fort Collins, Colorado.
- Karydis, M., and D. Kitsiou. 2013. Marine water quality monitoring: a review, *Marine Pollution Bulletin* 77:23–36.
- Knee, K. L., B. A. Layton, J. H. Street, A. B. Boehm, and A. Paytan. 2008. Sources of nutrients and fecal indicator bacteria to nearshore waters on the north shore of Kauai (Hawaii, USA). *Estuaries and Coasts*. 31(4)607–622.
- Knee, K. L., and A. Paytan. 2011. Submarine groundwater discharge: A source of nutrients, metals, and pollutants to the coastal ocean. Pages 205–234 in E. Wolanski and D. S. McLusky, editors. *Treatise on Estuarine and Coastal Science* 4. Academic Press, Waltham.
- Knee, K. L., J. H. Street, E. E., Grossman, A. B. Boehm, and A. Paytan, 2010. Nutrient inputs to the coastal ocean from submarine groundwater discharge in a groundwater-dominated system: Relation to land use (Kona coast, Hawaii, U.S.A). *Limnology and Oceanography*. 53:1105–1122.
- Knee, K. L., E. D. Crook, J. L. Hench, J. J. Leichter, and A. Paytan. 2016. Assessment of submarine groundwater discharge (SGD) as a source of dissolved radium and nutrients to Moorea (French Polynesia) coastal waters. *Estuaries and Coasts* 39(6):1651–1668.
- Kuznetsova, A., P. B. Brockhoff, R. H. B. Christensen. 2016. lmerTest: Tests in Linear Mixed Effects Models. R package version 2.0-33.
- Lau, L. S., and J. K. Mink. 2006. Hydrology of the Hawaiian Islands. University of Hawai‘i Press, Honolulu, Hawai‘i, USA.

- Li, L., D. A. Barry, F. Stagnitti, and J. Y. Parlange, 1999. Submarine groundwater discharge and associated chemical input to a coastal sea. *Water Resources Research*. 35(11):3253–3259.
- Lindenmayer, D. B., G. E. Likens, C. J. Krebs, and R. J. Hobbs. 2010. Improved probability of detection of ecological “surprises”. *Proceedings of the National Academy of Sciences* 107:21957–21962.
- McCook, L. J. 1999. Macroalgae, nutrients and phase shifts on coral reefs: scientific issues and management consequences for the Great Barrier Reef. *Coral Reefs* 18(4):357–367.
- Millard, S. 2013. *EnvStats*. Springer-Verlag, New York, New York.
- Minton, D., I. Lundgren, and A. Pakenham. 2007. A two-year study of coral recruitment and sedimentation in Asan Bay, Guam: Final report prepared for the National Park Service.
- Moore, W. S. 1999. The subterranean estuary: A reaction zone of ground water and sea water, *Chemistry* 65(1–2):111–125.
- Mueller, D. K., T. L. Schertz, J. D. Martin, and M. W. Sandstrom. 2015. Design, analysis, and interpretation of field quality-control data for water-sampling projects: U.S. Geological Survey Techniques and Methods, book 4, chap. C4, 54 p.
- NOAA. 2017. National Coral Reef Monitoring Program: Water Temperature Data from Subsurface Temperature Recorders (STRs) deployed at coral reef sites in the Hawaiian Archipelago from 2008-09-20 to 2013-09-14 Coral Reef Ecosystem Program; Pacific Islands Fisheries Science Center.
- NOAA. 2018. Oceanic Niño Index. http://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php, accessed June 2018.
- Oakley, K. L., L. P. Thomas, and S. G. Fancy. 2003. Guidelines for long-term monitoring protocols. *Wildlife Society Bulletin* 31:1000–1003.
- Oki, D. S. 1999. Geohydrology and numerical simulation of the ground-water flow system of Kona, Island of Hawaii. *Water-Resources Investigations Report* 99-4073. U.S. Geological Survey, Honolulu, Hawaii.
- Paerl, H. W., T. G. Otten, and R. Kudela. 2018. Mitigating the expansion of harmful algal blooms across the freshwater-to-marine continuum. *Environmental Science & Technology* 52(10):5519–5529. DOI: 10.1021/acs.est.7b05950.
- Paytan, A., G. G. Shellenbarger, J. H. Street, M. E. Gonneea, K. Davis, M. B. Young, and W. S. Moore. 2006. Submarine groundwater discharge: an important source of new inorganic nitrogen to coral reef ecosystems. *Limnology and Oceanography* 51(1):343–348.

- Peterson, R. N., W. C. Burnett, C. R., Glenn, and A. G. Johnson. 2009. Quantification of point-source groundwater discharges to the ocean from the shoreline of the Big Island, Hawaii, *Limnology and Oceanography* 54:890–904.
- Piepho, H., and J. O. Ogutu. 2002. A simple mixed model for trend analysis in wildlife populations. *Journal of Agricultural, Biological, and Environmental Statistics* 7(3):350–360.
- Pierce, D. W., P. J. Barnett, B. D. Santer, and P.J. Durack, 2012. The fingerprint of human-induced changes in the ocean's salinity and temperature fields. *Geophysical Research Letters* 39 L21704.
- Polis, A., and M. E. Power, Eds. 2004. Food webs at the landscape level. Chicago: University of Chicago Press.
- Porter, V., T. Leberer, M. Gawel, J. Gutierrez, D. Burdick, V. Torres, E. Lujan. 2005. The State of Coral Reef Ecosystems of Guam. The State of the Coral Reef Ecosystems of the United States and Pacific Freely Associated States.
- R Core Team. 2017. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL <https://www.R-project.org/>.
- Raikow, D. F., A. Farahi, S. Kichman, and A. L. McCutcheon. 2017. Marine water quality in in Kaloko-Honokōhau National Historical Park: Summary report 2008-2014. Natural Resource Data Series NPS/PACN/NRDS—2017/1092. National Park Service, Fort Collins, Colorado.
- Raikow, D. F., A. Farahi, A.L. McCutcheon, E. Brown, and S. Kichman. 2017. Marine water quality in in Kalaupapa National Historical Park Summary Report 2008-2014. Natural Resource Data Series NPS/PACN/NRDS—2017/1120. National Park Service, Fort Collins, Colorado.
- Raikow, D. F., A. Farahi, A. L. McCutcheon, B. Fuiava, V. Vaivai and S. Kichman. 2017. Marine water quality in National Park of American Samoa Summary Report 2009-2014. Natural Resource Data Series NPS/PACN/NRDS—2017/1121. National Park Service, Fort Collins, Colorado.
- Raikow, D. F., A. Farahi, A. L. McCutcheon and S. Kichman. 2017. Marine water quality in War in the Pacific National Historical Park Summary Report 2009-2014. Natural Resource Data Series NPS/PACN/NRDS—2017/1122. National Park Service, Fort Collins, Colorado.
- Robinson, C., L. Li, and H. Prommer (2007), Tide-induced recirculation across the aquifer-ocean interface, *Water Resources Research*, 43, W07428, doi:10.1029/2006WR005679
- Rupic, M., L. Wetzell, J. J. Marra, and S. Balwani, 2018, 2014–2016 El Niño Assessment Report, NOAA National Centers for Environmental Information, Honolulu, HI, USA.
- Sardans, J., Rivas-Ubach, A. and Penuelas, J., 2012. The elemental stoichiometry of aquatic and terrestrial ecosystems and its relationships with organismic lifestyle and ecosystem structure and function: a review and perspectives. *Biogeochemistry*, 111(1–3), pp.1–39.

- Skalski, J.R., 1990. A design for long-term status and trends monitoring. *Journal of Environmental Management*, 30(2), pp.139–144.
- Slomp, C.P. and Van Cappellen, P., 2004. Nutrient inputs to the coastal ocean through submarine groundwater discharge: controls and potential impact. *Journal of Hydrology*, 295(1–4), pp.64–86.
- Smil, Vaclav. 2000. "Phosphorus in the environment: natural flows and human interferences." *Annual review of energy and the environment* 25, no. 1 (2000): 53–88.
- Starceovich L.A.H. 2013. Trend and power analysis for National Park Service marine data from 2006 to 2010: Pacific Island Network. Natural Resource Technical Report NPS/PACN/MRTR—2013/771. National Park Service, Fort Collins, Colorado.
- Starceovich, L.A.H., McDonald, T. Chung-MacCoubrey, A., Heard, A., Nesmith, J., and Philippi, T., 2018. Methods for estimating trend in continuous response variables from complex survey designs. Natural Resource Report NPS/NRSS/IMD/NRR—2018/1584. National Park Service, Fort Collins, Colorado.
- Storlazzi, C.D., Presto, M.K., and Logan, J.B., 2009. "Coastal Circulation and Sediment Dynamics in War-in-the-Pacific National Historical Park, Guam. Measurements of Waves, Currents, Temperature, Salinity, and Turbidity: June 2007–January 2008." USGS Open-File Report 2009-1195
- Storlazzi, C.D., Cheriton, O.M., Lescinski, J.M.R., and Logan, J.B., 2014, Coastal circulation and water-column properties in the War in the Pacific National Historical Park, Guam—Measurements and modeling of waves, currents, temperature, salinity, and turbidity, April–August 2012: U.S. Geological Survey Open-File Report 2014-1130, 104 p., <http://dx.doi.org/10.3133/ofr20141130>.
- Storlazzi, C.D., Shope, J.B., Erikson, L.H., Hegermiller, C.A., and Barnard, P.L., 2015, Future wave and wind projections for United States and United States-affiliated Pacific Islands: U.S. Geological Survey Open-File Report 2015–1001, 426 p., <http://dx.doi.org/10.3133/ofr20151001>.
- Street, J.H., Knee, K.L., Grossman, E.E. and Paytan, A., 2008. Submarine groundwater discharge and nutrient addition to the coastal zone and coral reefs of leeward Hawai'i. *Marine Chemistry*, 109(3–4), pp.355–376.
- Sutton, J., N. Luchetti, E. Wright, M. C. Kruk, J. J. Marra, 2016, An El Niño Southern Oscillation (ENSO) Based Precipitation Climatology for the United States Affiliated Pacific Islands (USAPI) using the PERSIANN Climate Data Record (CDR), NOAA's National Centers for Environmental Information, Asheville, NC, USA.
- Taboroši, D., J. W. Jenson, and J. E. Mylororie, 2004. Karst Features of Guam Mariana Islands, Technical Report No. 104, Water & Environmental Research Institute of the Western Pacific, University of Guam.

- Taniguchi, M., 2002 Tidal effects on submarine groundwater discharge into the ocean, *Geophysical Research Letters*, 29:1–3.
- Taniguchi, M., Burnett, W.C., Cable, J.E. and Turner, J.V., 2002. Investigation of submarine groundwater discharge. *Hydrological Processes*, 16(11), pp.2115–2129.
- Thorpe, S.A. 2007, *An Introduction to Ocean Turbulence*, Cambridge University Press, Cambridge, UK.
- Urquhart, N.S., Paulsen, S.G. and Larsen, D.P., 1998. Monitoring for policy-relevant regional trends over time. *Ecological Applications*, 8(2), pp.246–257.
- VanLeeuwen D.M., L.W. Murray, and N.S. Urquhart. 1996. A mixed model with both fixed and random trend components across time. *Journal of Agricultural, Biological, and Environmental Statistics* 1(4): 435–453.
- Vincent, D.G., 1994. The South Pacific convergence zone (SPCZ): A review. *Monthly Weather Review*, 122(9), pp.1949–1970.
- Vitousek, P. M., Mooney, H. A., Lubchenco, J., & Melillo, J. M. (1997). Human domination of Earth's ecosystems. *Science*, 277(5325), 494–499.
- Walsh, W., R. Sparks, C. Barnett, C. Couch, S. Cotton, D. White, K. stone, and E. Conklin. 2009. Long-term monitoring of coral reefs of the main Hawaiian islands, State of Hawai'i Monitoring Report NA06NOS4260113, Hawai'i Division of Aquatic Resources, Department of Land and Natural Resources, Honolulu, HI.
- Wang, C., C. Deser, J.-Y. Yu, P. DiNezio, and A. Clement. 2016. El Niño-Southern Oscillation (ENSO): A review. In *Coral Reefs of the Eastern Pacific*, P. Glynn, D. Manzello, and I. Enochs, Eds., Springer Science Publisher, 85–106.
- Wiegner. T. N., C. J. Edens, L. M. Abaya, K. M. Carlson, A. Lyon-Colbert, and S. L. Molloy. 2017. Spatial and temporal microbial pollution patterns in a tropical estuary during high and low river flow conditions, *Marine Pollution Bulletin* 114(2):952–961.
- Weissinger, R., and D. Sharrow. 2018. Status and trends of water quality at Zion National Park: Water years 2006–2016 (rev. June 2018). Natural Resource Report NPS/NCPN/NRR2018/1670. National Park Service, Fort Collins, Colorado.
- Wong, J., C. W. Y. Chen, K. C. Chung, 1998. Nitrogen and Phosphorus leaching from Fertilizer applied on golf course: lysimeter study, *Water, Air, & Soil Pollution* 107:335.
- Yu, L., 2011. A global relationship between the ocean water cycle and near-surface salinity, *Journal of Geophysical Research* 116:1–17.
- Ziegler, A. C., 2002. *Hawaiian natural history, ecology, and evolution*. University of Hawaii Press.

Appendix A. R code

R Script for Linear Mixed Model (Example KALA)

```
library(lmerTest) #Must use this instead of lmer4 to get p-values
library(ggplot2)
library(xlsx) #Had to install rJava and xlsxJars before installing
xlsx

# Set working directory
setwd("C:/Users/ALMccutcheon/Documents/VitalSigns/WaterQuality/MarineTrendReports/Data")

# Input data
nutdata <- read.csv("KALAMarineNutrientsforR_20082015.csv",
header=TRUE)
ysidata <- read.csv("KALAMarineYSIforR_20082015.csv", header=TRUE)

# Parameters for input. Used to automate the loops below.
ParamNut <- c("TDP","TDN","NO3") #Typed these out because we don't
want to analyze TN and TP at the moment
ParamYSI<-unlist(unique(ysidata["Parameter_short"]))
ParamYSI<-ParamYSI[ParamYSI!="Depth"]

Depths<-unlist(unique(nutdata["Depth"]))
#List of Regularly sampled fixed stations
FixedStations <-
c("FKALA03_mr","FKALA06_mr","FKALA11_mr","FKALA14_mr")

# Create WYear which starts at Year Zero
nutdata["WYear"] <- nutdata["Year.Quarter"]-min(nutdata["Year"])
ysidata["WYear"] <- ysidata["Year.Quarter"]-min(ysidata["Year"])

#### Nutrient Loop #### Runs once for each nutrient parameter.
for(i in ParamNut)
{
  ## Raw
  SelectData <- nutdata[nutdata$Parameter==i,]

  # Perform Linear Mixed Models for Nutrients
  # Nut MixedModel is linear mixed model with both depths
  included. Factors included are WYear (time), Depth, quarter, season
  (wet/dry), year, and site
  # Bottom/SurfaceNutMixed model is similar but data used are
  only from the specific depth
```

```

    NutMixedModel <-
lmer(log(Mean)~WYear*Depth+(1|Year)+(1+WYear|Station_ID),data=SelectData)
    #Fixed only for Bottom/Surface Analysis because otherwise
there are too many random factors
    FixedSelectData<-
SelectData[grep("^FKALA",SelectData$Station_ID),]
    BottomNutMixedModel <-
lmer(log(Mean)~WYear+(1|Year)+(1+WYear|Station_ID),data=FixedSelectData[FixedSelectData$Depth=="Bottom",])
    SurfaceNutMixedModel <-
lmer(log(Mean)~WYear+(1|Year)+(1+WYear|Station_ID),data=FixedSelectData[FixedSelectData$Depth=="Surface",])

    #Create Summary Tables and assign to unique variable name
NutSum <-summary(NutMixedModel)$coefficients
assign(paste("Summary",i,"All",sep=' '),NutSum)
BottomNutSum <-summary(BottomNutMixedModel)$coefficients
assign(paste("Summary",i,"Bottom",sep=' '),BottomNutSum)
SurfaceNutSum <-summary(SurfaceNutMixedModel)$coefficients
assign(paste("Summary",i,"Surface",sep=' '),SurfaceNutSum)

    #Make a xlsx workbook for each parameter using the Summary
Tables above.
write.xlsx(NutSum,file=paste(i,"LmerSummary.xlsx",sep=' '),sheetName="All",append=FALSE)
    write.xlsx(BottomNutSum,file=paste(i,"LmerSummary.xlsx",sep=' '),sheetName="Fixed Bottom",append=TRUE)
    write.xlsx(SurfaceNutSum,file=paste(i,"LmerSummary.xlsx",sep=' '),sheetName="Fixed Surface",append=TRUE)

    #Examine Residuals
    #Create ResidDiagnostic fuction and run for each model.
ResidDiagnostic<-function(fit){
  par(mfrow=c(2,2))
  plot(fitted(fit),resid(fit))
  qqnorm(resid(fit))
  hist(resid(fit))
  title(main=paste(i,deparse(substitute(fit)),"Residual
Plots",sep=' '),outer=T,line=-1)
}

ResidDiagnostic(NutMixedModel)
ResidDiagnostic(BottomNutMixedModel)

```

```

    ResidDiagnostic(SurfaceNutMixedModel)
}

#### YSI Loop #### Runs once for each YSI parameter.
# Used Corrected Mean for all parameters

for (k in ParamYSI)
{
  ## Raw
  SelectData <- ysidata[ysidata$Parameter_short==k,]

  # Perform Linear Mixed Model for YSI Parameters
  YsiMixedModel <-
lmer(Corrected_Mean~WYear*Depth+(1|Year)+(1+WYear|Station_ID),data=
SelectData)

  #Fixed only for Bottom/Surface Analysis because otherwise
there are too many random factors
  FixedSelectData<-
SelectData[grepl("^FKALA",SelectData$Station_ID),]
  BottomYsiMixedModel <-
lmer(Corrected_Mean~WYear+(1|Year)+(1+WYear|Station_ID),data=FixedS
electData[FixedSelectData$Depth=="Bottom",])
  SurfaceYsiMixedModel <-
lmer(Corrected_Mean~WYear+(1|Year)+(1+WYear|Station_ID),data=FixedS
electData[FixedSelectData$Depth=="Surface",])

  #Alternate Model for Sal and Temp that includes the seasonal
elements
  if(k=="Sal" || k=="Temp") {
    YsiMixedModel <-
lmer(Corrected_Mean~WYear*Depth+Quarter+Season+(1|Year)+(1+WYear|St
ation_ID),data=SelectData)
    BottomYsiMixedModel <-
lmer(Corrected_Mean~WYear+Quarter+Season+(1|Year)+(1+WYear|Station_
ID),data=FixedSelectData[FixedSelectData$Depth=="Bottom",])
    SurfaceYsiMixedModel <-
lmer(Corrected_Mean~WYear+Quarter+Season+(1|Year)+(1+WYear|Station_
ID),data=FixedSelectData[FixedSelectData$Depth=="Surface",])
  }

  # Alternate Model for DO Concentration that includes wet and
dry season
  if(k=="ODOConc") {

```

```

    YsiMixedModel <-
lmer(Corrected_Mean~WYear*Depth+Season+(1|Year)+(1+WYear|Station_ID)
),data=SelectData)
    BottomYsiMixedModel <-
lmer(Corrected_Mean~WYear+Season+(1|Year)+(1+WYear|Station_ID),data
=FixedSelectData[FixedSelectData$Depth=="Bottom",])
    SurfaceYsiMixedModel <-
lmer(Corrected_Mean~WYear+Season+(1|Year)+(1+WYear|Station_ID),data
=FixedSelectData[FixedSelectData$Depth=="Surface",])
  }

  #Create Summary Table and assign to unique variable name
  YsiSum <-summary(YsiMixedModel)$coefficients
  assign(paste("Summary",k,"All",sep=' '),YsiSum)
  BottomYsiSum <-summary(BottomYsiMixedModel)$coefficients
  assign(paste("Summary",k,"Bottom",sep=' '),BottomYsiSum)
  SurfaceYsiSum <-summary(SurfaceYsiMixedModel)$coefficients
  assign(paste("Summary",k,"Surface",sep=' '),SurfaceYsiSum)

  #Make a xlsx workbook for each parameter using the Summary
  Tables above. Each pool group gets its own tab
  write.xlsx(YsiSum,file=paste(k,"LmerSummary.xlsx",sep=' '),shee
tName="All",append=FALSE)
  write.xlsx(BottomYsiSum,file=paste(k,"LmerSummary.xlsx",sep=' '
),sheetName="Fixed Bottom",append=TRUE)
  write.xlsx(SurfaceYsiSum,file=paste(k,"LmerSummary.xlsx",sep='
'),sheetName="Fixed Surface",append=TRUE)

  #Examine Residuals
  ResidDiagnostic<-function(fit){
    par(mfrow=c(2,2))
    plot(fitted(fit),resid(fit))
    qqnorm(resid(fit))
    hist(resid(fit))
    title(main=paste(k,deparse(substitute(fit)),"Residual
Plots",sep=' '),outer=T,line=-1)
  }

  ResidDiagnostic(YsiMixedModel)
  ResidDiagnostic(BottomYsiMixedModel)
  ResidDiagnostic(SurfaceYsiMixedModel)
}

```

R Script for Seasonality Analysis (Example KAHO)

```
ParamNut <- c("TDN","TDP","NO3")
ParamYSI <-c("Chl","DOconc","DOsat","pH","Sal","SpC","Temp","Turb")
ParamFull <- c("Chlorophyll","Dissolved Oxygen
Concentration","Dissolved Oxygen
Saturation","pH","Salinity","Specific
conductance","Temperature","Turbidity")

# set working directory
setwd("C:/Users/ALMccutcheon@NPS.GOV/Documents/VitalSigns/WaterQual
ity/MarineTrendReports/Data")

#Get Datasets for Nutrients and YSI

nutdata <- read.csv("KAHOMarineNutrientsforR_20082015.csv",
header=TRUE)

ysidata <- read.csv("KAHOMarineYSIforR_20082015.csv", header=TRUE)

# Create seasonal columns
q1 <- nutdata$Quarter=="1"
q2 <- nutdata$Quarter=="2"
q3 <- nutdata$Quarter=="3"
q4 <- nutdata$Quarter=="4"
dry <- nutdata$Season=="Dry"
wet <- nutdata$Season=="Wet"

seasonalnutdata <-
data.frame(nutdata,"q1"=q1+0,"q2"=q2+0,"q3"=q3+0,"q4"=q4+0,"dry"=dr
y+0,"wet"=wet+0)

q1 <- ysidata$Quarter=="1"
q2 <- ysidata$Quarter=="2"
q3 <- ysidata$Quarter=="3"
q4 <- ysidata$Quarter=="4"
dry <- ysidata$Season=="Dry"
wet <- ysidata$Season=="Wet"

seasonalysidata <-
data.frame(ysidata,"q1"=q1+0,"q2"=q2+0,"q3"=q3+0,"q4"=q4+0,"dry"=dr
y+0,"wet"=wet+0)

#Separate Bottom and Surface Data
Surnutdata <- seasonalnutdata[nutdata$Depth=="Surface",]
Botnutdata <- seasonalnutdata[nutdata$Depth=="Bottom",]
```

```

SurySIData <- seasonalsIData[ysIData$Depth=="Surface",]
BotSIData <- seasonalsIData[ysIData$Depth=="Bottom",]

# Each Subsection below I first separate data for the specified
parameter.
# Next I create a dataset averaged by Year.Quarter by separating,
aggregating,
# and then re-merging the surface and bottom data back into one
dataset before
# performing the seasonality analyses on this time series data.
Four analyses are run:
# 1. season based on four quarters
# 2. season based on Wet and Dry seasons
# 3. 4 quarters for only surface samples
# 4. Wet/Dry for only surface samples

#### Nutrient Loop #### Runs once for each nutrient parameter.

for(i in ParamNut)
{
## Year.Quarter Averaged
sdataforagg <-
Surnutdata[Surnutdata$Parameter==i,][c("Year","Quarter","Year.Quart
er","Mean","StDev","SE","wet","dry","q1","q2","q3","q4")]
bdataforagg <-
Botnutdata[Botnutdata$Parameter==i,][c("Year","Quarter","Year.Quart
er","Mean","StDev","SE","wet","dry","q1","q2","q3","q4")]

sdata <-
aggregate(sdataforagg,by=list(sdataforagg["Year.Quarter"][,1]),FUN=
"mean")
bdata <-
aggregate(bdataforagg,by=list(bdataforagg["Year.Quarter"][,1]),FUN=
"mean")

Datamerged <-
rbind(data.frame(sdata,"Depth"=rep("Surface",nrow(sdata))),data.fra
me(bdata,"Depth"=rep("Bottom",nrow(bdata))))

#Seasonality (quarters) by multiple regression for averaged data.

avgregquarters <- lm(Mean ~ Year.Quarter + q1 + q2 + q3,
data=Datamerged)
f<-summary(avgregquarters)$fstatistic

```

```

pavgq <- pf(f[1], f[2], f[3], lower=FALSE)
assign(paste("p",i,"avgq",sep=""),pavgq)
pvaluesavgq <- coef(summary(avgregquarters))[,4]
assign(paste("pvals",i,"avgq",sep=""),pvaluesavgq)
ravgq <- summary(avgregquarters)$r.squared
assign(paste("r2",i,"avgq",sep=""),ravgq)

#Seasonality (wet/dry) by multiple regression for averaged data.

avgregwetdry <- lm(Mean ~ Year.Quarter + wet, data=Datamerged)
f<-summary(avgregwetdry)$fstatistic
pavgwet <- pf(f[1], f[2], f[3], lower=FALSE)
assign(paste("p",i,"avgwet",sep=""),pavgwet)
pvaluesavgwet <- coef(summary(avgregwetdry))[,4]
assign(paste("pvals",i,"avgwet",sep=""),pvaluesavgwet)
ravgwet <- summary(avgregwetdry)$r.squared
assign(paste("r2",i,"avgwet",sep=""),ravgwet)

#Seasonality (quarters) by multiple regression for averaged surface
data.

avgregquarterssur <- lm(Mean ~ Year.Quarter + q1 + q2 + q3,
data=Datamerged[Datamerged$Depth=="Surface",])
f<-summary(avgregquarterssur)$fstatistic
pavgqsur <- pf(f[1], f[2], f[3], lower=FALSE)
assign(paste("p",i,"avgqsur",sep=""),pavgqsur)
pvaluesavgqsur <- coef(summary(avgregquarterssur))[,4]
assign(paste("pvals",i,"avgqsur",sep=""),pvaluesavgqsur)
ravgqsur <- summary(avgregquarterssur)$r.squared
assign(paste("r2",i,"avgqsur",sep=""),ravgqsur)

#Seasonality (wet/dry) by multiple regression for averaged surface
data.

avgregwetdrysur <- lm(Mean ~ Year.Quarter + wet,
data=Datamerged[Datamerged$Depth=="Surface",])
f<-summary(avgregwetdrysur)$fstatistic
pavgwetsur <- pf(f[1], f[2], f[3], lower=FALSE)
assign(paste("p",i,"avgwetsur",sep=""),pavgwetsur)
pvaluesavgwetsur <- coef(summary(avgregwetdrysur))[,4]
assign(paste("pvals",i,"avgwetsur",sep=""),pvaluesavgwetsur)
ravgwetsur <- summary(avgregwetdrysur)$r.squared
assign(paste("r2",i,"avgwetsur",sep=""),ravgwetsur)
}

```

```

#### YSI Loop #### Runs once for each YSI parameter.
for (k in ParamYSI)
{
  ## Year.Quarter Averaged
  sdataforagg <-
  Surysidata[Surysidata$Parameter==ParamFull[match(k,ParamYSI)],][c("
Year","Quarter","Year.Quarter","Corrected_Mean","wet","dry","q1","q
2","q3","q4")]
  bdataforagg <-
  Botysidata[Botysidata$Parameter==ParamFull[match(k,ParamYSI)],][c("
Year","Quarter","Year.Quarter","Corrected_Mean","wet","dry","q1","q
2","q3","q4")]

  sdata <-
  aggregate(sdataforagg,by=list(sdataforagg["Year.Quarter"][,1]),FUN=
"mean")
  bdata <-
  aggregate(bdataforagg,by=list(bdataforagg["Year.Quarter"][,1]),FUN=
"mean")

  DatamergedYSI <-
  rbind(data.frame(sdata,"Depth"=rep("Surface",nrow(sdata))),data.fra
me(bdata,"Depth"=rep("Bottom",nrow(bdata))))
  #Seasonality (quarters) by multiple regression for averaged
data.

  avgregquarters <- lm(Corrected_Mean ~ Year.Quarter + q1 + q2 +
q3, data=DatamergedYSI)
  f<-summary(avgregquarters)$fstatistic
  pavgq <- pf(f[1], f[2], f[3], lower=FALSE)
  assign(paste("p",k,"avgq",sep=' '),pavgq)
  pvaluesavgq <- coef(summary(avgregquarters))[,4]
  assign(paste("pvals",k,"avgq",sep=' '),pvaluesavgq)
  ravgq <- summary(avgregquarters)$r.squared
  assign(paste("r2",k,"avgq",sep=' '),ravgq)

  #Seasonality (wet/dry) by multiple regression for averaged
data.

  avgregwetdry <- lm(Corrected_Mean ~ Year.Quarter + wet,
data=DatamergedYSI)
  f<-summary(avgregwetdry)$fstatistic
  pavgwet <- pf(f[1], f[2], f[3], lower=FALSE)
  assign(paste("p",k,"avgwet",sep=' '),pavgwet)

```

```

pvaluesavgwet <- coef(summary(avgregwetdry))[,4]
assign(paste("pvals",k,"avgwet",sep=" "),pvaluesavgwet)
ravgwet <- summary(avgregwetdry)$r.squared
assign(paste("r2",k,"avgwet",sep=" "),ravgwet)

#Seasonality (quarters) by multiple regression for averaged
surface data.

avgregquarterssur <- lm(Corrected_Mean ~ Year.Quarter + q1 +
q2 + q3, data=DatamergedYSI[DatamergedYSI$Depth=="Surface",])
f<-summary(avgregquarterssur)$fstatistic
pavgqsur <- pf(f[1], f[2], f[3], lower=FALSE)
assign(paste("p",k,"avgqsur",sep=" "),pavgqsur)
pvaluesavgqsur <- coef(summary(avgregquarterssur))[,4]
assign(paste("pvals",k,"avgqsur",sep=" "),pvaluesavgqsur)
ravgqsur <- summary(avgregquarterssur)$r.squared
assign(paste("r2",k,"avgqsur",sep=" "),ravgqsur)

#Seasonality (wet/dry) by multiple regression for averaged
surface data.

avgregwetdrysur <- lm(Corrected_Mean ~ Year.Quarter + wet,
data=DatamergedYSI[DatamergedYSI$Depth=="Surface",])
f<-summary(avgregwetdrysur)$fstatistic
pavgwetsur <- pf(f[1], f[2], f[3], lower=FALSE)
assign(paste("p",k,"avgwetsur",sep=" "),pavgwetsur)
pvaluesavgwetsur <- coef(summary(avgregwetdrysur))[,4]
assign(paste("pvals",k,"avgwetsur",sep=" "),pvaluesavgwetsur)
ravgwetsur <- summary(avgregwetdrysur)$r.squared
assign(paste("r2",k,"avgwetsur",sep=" "),ravgwetsur)

}

#### Make Results Tables ####

Parameters <- c(ParamNut,ParamYSI)

p_value <-
round(rbind(pTDNavgq,pTDPavgq,pNO3avgq,pChlavgq,pDOconavgq,pDOsata
vgq,ppHavgq,pSalavgq,pSpCavgq,pTempavgq,pTurbavgq),digits=3)
KAHOREgavgQResults<-data.frame(Parameters,p_value)

p_value <-
round(rbind(pTDNavgwet,pTDPavgwet,pNO3avgwet,pChlavgwet,pDOconavgw

```

```

et,pDOsatavgwet,ppHavgwet,pSalavgwet,pSpCavgwet,pTempavgwet,pTurbav
gwet),digits=3)
KAHOREgavgwetResults<-data.frame(Parameters,p_value)

p_value <-
round(rbind(pTDNavgqsur,pTDPavgqsur,pNO3avgqsur,pChlavgqsur,pDOconc
avgqsur,pDOsatavgqsur,ppHavgqsur,pSalavgqsur,pSpCavgqsur,pTempavgqs
ur,pTurbavgqsur),digits=3)
KAHOREgavgQResultssur<-data.frame(Parameters,p_value)

p_value <-
round(rbind(pTDNavgwetsur,pTDPavgwetsur,pNO3avgwetsur,pChlavgwetsur
,pDOconccavgwetsur,pDOsatavgwetsur,ppHavgwetsur,pSalavgwetsur,pSpCav
gwetsur,pTempavgwetsur,pTurbavgwetsur),digits=3)
KAHOREgavgwetResultssur<-data.frame(Parameters,p_value)
####

p_values <-
round(rbind(pvalsTDNavgq,pvalsTDPavgq,pvalsNO3avgq,pvalsChlavgq,pva
lsDOconccavgq,pvalsDOsatavgq,pvalspHavgq,pvalsSalavgq,pvalsSpCavgq,p
valsTempavgq,pvalsTurbavgq),digits=3)
KAHOREgavgQPvals<-data.frame(Parameters,p_values)

p_values <-
round(rbind(pvalsTDNavgwet,pvalsTDPavgwet,pvalsNO3avgwet,pvalsChlav
gwet,pvalsDOconccavgwet,pvalsDOsatavgwet,pvalspHavgwet,pvalsSalavgwe
t,pvalsSpCavgwet,pvalsTempavgwet,pvalsTurbavgwet),digits=3)
KAHOREgavgwetPvals<-data.frame(Parameters,p_values)

p_values <-
round(rbind(pvalsTDNavgqsur,pvalsTDPavgqsur,pvalsNO3avgqsur,pvalsCh
lavgqsur,pvalsDOconccavgqsur,pvalsDOsatavgqsur,pvalspHavgqsur,pvalsS
alavgqsur,pvalsSpCavgqsur,pvalsTempavgqsur,pvalsTurbavgqsur),digits
=3)
KAHOREgavgQPvalssur<-data.frame(Parameters,p_values)

p_values <-
round(rbind(pvalsTDNavgwetsur,pvalsTDPavgwetsur,pvalsNO3avgwetsur,p
valsChlavgwetsur,pvalsDOconccavgwetsur,pvalsDOsatavgwetsur,pvalspHav
gwetsur,pvalsSalavgwetsur,pvalsSpCavgwetsur,pvalsTempavgwetsur,pval
sTurbavgwetsur),digits=3)
KAHOREgavgwetPvalssur<-data.frame(Parameters,p_values)

####

```

```

R2 <-
round(rbind(r2TDNavgq,r2TDPavgq,r2NO3avgq,r2Chlavgq,r2DOconavgq,r2
DOsatavgq,r2pHavgq,r2Salavgq,r2SpCavgq,r2Tempavgq,r2Turbavgq),digit
s=3)
KAHOREgavgQr2<-data.frame(Parameters,R2)

R2 <-
round(rbind(r2TDNavgwet,r2TDPavgwet,r2NO3avgwet,r2Chlavgwet,r2DOcon
cavgwet,r2DOSatavgwet,r2pHavgwet,r2Salavgwet,r2SpCavgwet,r2Tempavgw
et,r2Turbavgwet),digits=3)
KAHOREgavgwetr2<-data.frame(Parameters,R2)

R2 <-
round(rbind(r2TDNavgqsur,r2TDPavgqsur,r2NO3avgqsur,r2Chlavgqsur,r2D
Oconavgqsur,r2DOSatavgqsur,r2pHavgqsur,r2Salavgqsur,r2SpCavgqsur,r
2Tempavgqsur,r2Turbavgqsur),digits=3)
KAHOREgavgQr2sur<-data.frame(Parameters,R2)

R2 <-
round(rbind(r2TDNavgwetsur,r2TDPavgwetsur,r2NO3avgwetsur,r2Chlavgwe
tsur,r2DOconavgwetsur,r2DOSatavgwetsur,r2pHavgwetsur,r2Salavgwetsu
r,r2SpCavgwetsur,r2Tempavgwetsur,r2Turbavgwetsur),digits=3)
KAHOREgavgwetr2sur<-data.frame(Parameters,R2)

# Make Tables for Each Park Combining All P-values

KAHOAllRegavgQ<-cbind(Parameters,"p
main"=KAHOREgavgQResults$value,KAHOREgavgQPvals[, -
(1:2)],"R2"=KAHOREgavgQr2[, -1])

KAHOAllRegavgwet<-cbind(Parameters,"p
main"=KAHOREgavgwetResults$value,KAHOREgavgwetPvals[, -
(1:2)],"R2"=KAHOREgavgwetr2[, -1])

KAHOAllRegavgQsur<-cbind(Parameters,"p
main"=KAHOREgavgQResultssur$value,KAHOREgavgQPvalssur[, -
(1:2)],"R2"=KAHOREgavgQr2sur[, -1])

KAHOAllRegavgwetsur<-cbind(Parameters,"p
main"=KAHOREgavgwetResultssur$value,KAHOREgavgwetPvalssur[, -
(1:2)],"R2"=KAHOREgavgwetr2sur[, -1])

# Make Combined Results Tables

AllResultsRegavgQ <- cbind(Parameters,"KAHO"=KAHOAllRegavgQ[, -1])

```

```

AllResultsRegavgwet <- cbind(Parameters,"KAHO"=KAHOAllRegavgwet[,-
1])
AllResultsRegavgQsur <-
cbind(Parameters,"KAHO"=KAHOAllRegavgQsur[,-1])
AllResultsRegavgwetsur <-
cbind(Parameters,"KAHO"=KAHOAllRegavgwetsur[,-1])

AllResultsRegavgQ=
  data.frame(KAHOAllRegavgQ, Park = 'KAHO', Parameter =
factor(KAHOAllRegavgQ$Parameters, levels =
KAHOAllRegavgQ$Parameters),
  row.names = NULL,check.names = FALSE)

PTabAvgQuarters <- tabular(Heading()* Parameter ~ Park *(`R2`+`p
main`
+`Year.Quarter`+`q1`+`q2`+`q3`)*Heading()*(identity),data=AllResult
sRegavgQ)
write.csv.tabular(PTabAvgQuarters,"KAHOPTabAvgQuarters.csv")

AllResultsRegavgwet=
  data.frame(KAHOAllRegavgwet, Park = 'KAHO', Parameter =
factor(KAHOAllRegavgwet$Parameters, levels =
KAHOAllRegavgwet$Parameters),
  row.names = NULL,check.names = FALSE)
  row.names = NULL,check.names = FALSE)

PTabavgWetDry <- tabular(Heading()* Parameter ~ Park *(`R2`+`p
main`
+`Year.Quarter`+`wet`)*Heading()*(identity),data=AllResultsRegavgwe
t)
write.csv.tabular(PTabavgWetDry,"KAHOPTabavgWetDry.csv")

AllResultsRegavgQsur=
  data.frame(KAHOAllRegavgQsur, Park = 'KAHO', Parameter =
factor(KAHOAllRegavgQsur$Parameters, levels =
KAHOAllRegavgQsur$Parameters),
  row.names = NULL,check.names = FALSE)

PTabAvgQuarterssur <- tabular(Heading()* Parameter ~ Park *(`R2`+`p
main`
+`Year.Quarter`+`q1`+`q2`+`q3`)*Heading()*(identity),data=AllResult
sRegavgQsur)
write.csv.tabular(PTabAvgQuarterssur,"KAHOPTabAvgQuarterssur.csv")

```

```

AllResultsRegavgwetsur=
  data.frame(KAHOAllRegavgwetsur, Park = 'KAHO', Parameter =
factor(KAHOAllRegavgwetsur$Parameters, levels =
KAHOAllRegavgwetsur$Parameters),
  row.names = NULL,check.names = FALSE)

PTabavgWetDrysor <- tabular(Heading()* Parameter ~ Park *(`R2`+'p
main`
+'Year.Quarter`+'wet`)*Heading()*(identity),data=AllResultsRegavgwe
tsur)
write.csv.tabular(PTabavgWetDrysor,"KAHOPTabavgWetDrysor.csv")

```

R Script for Surface/Bottom Correlation Analyses (Example WAPA – Agat)

```
# set working directory
setwd("C:/Users/ALMccutcheon@NPS.GOV/Documents/VitalSigns/WaterQuality/MarineTrendReports/Data")

#Get Datasets for Nutrients and YSI
nutdata <- read.csv("AgatMarineNutrientsforR_Test.csv",
header=TRUE)
ysidata <- read.csv("AgatMarineYSIforR_Test.csv", header=TRUE)

ParamNut <- c("NO3", "TDN", "TDP")
ParamYSI <- c("Chl", "DOconc", "DOsat", "pH", "Sal", "SpC", "Temp",
"Turb")
ParamFull <- c("Chlorophyll", "Dissolved Oxygen
Concentration", "Dissolved Oxygen
Saturation", "pH", "Salinity", "Specific
conductance", "Temperature", "Turbidity")

# Each Subsection below first separates data for the specified
parameter,
# then aggregates the data and averages by Year.Quarter,
# then merges the surface and bottom data back into one dataset
before
# performing a Pearson Correlation test.

##Nutrient Loop##

for( i in ParamNut){

SelectData <- nutdata[nutdata$Parameter==i,]
#Separate Bottom and Surface Data
Surnutdata <- SelectData[SelectData$Depth=="Surface",]
Botnutdata <- SelectData[SelectData$Depth=="Bottom",]

sdataforagg <-
Surnutdata[c("Year", "Quarter", "Year.Quarter", "Mean", "StDev", "SE")]
bdataforagg <-
Botnutdata[c("Year", "Quarter", "Year.Quarter", "Mean", "StDev", "SE")]

sdata <-
aggregate(sdataforagg, by=list(sdataforagg["Year.Quarter"][,1]), FUN=
"mean")
```

```

bdata <-
aggregate(bdataforagg,by=list(bdataforagg["Year.Quarter"][,1]),FUN=
"mean")

datamerged <- merge(sdata,bdata,by="Year.Quarter")

#Pearsons Correlation
cor <- cor.test(datamerged$Mean.x, datamerged$Mean.y, method =
"pearson")
assign(paste(i,"cor",sep=""),cor)
}

## YSI Loop ##
for(k in ParamYSI){
SelectData <-
ysidata[ysidata$Parameter==ParamFull[match(k,ParamYSI)],]

SurySIData <- SelectData[SelectData$Depth=="Surface",]
Botysidata <- SelectData[SelectData$Depth=="Bottom",]

sdataforagg <-
SurySIData[c("Year","Quarter","Year.Quarter","Corrected_Mean")]
bdataforagg <-
Botysidata[c("Year","Quarter","Year.Quarter","Corrected_Mean")]

sdata <-
aggregate(sdataforagg,by=list(sdataforagg["Year.Quarter"][,1]),FUN=
"mean")
bdata <-
aggregate(bdataforagg,by=list(bdataforagg["Year.Quarter"][,1]),FUN=
"mean")

datamerged <- merge(sdata,bdata,by="Year.Quarter")

#Pearsons Correlation
cor <- cor.test(datamerged$Corrected_Mean.x,
datamerged$Corrected_Mean.y, method = "pearson")
assign(paste(k,"cor",sep=""),cor)
}

## Print Table of Final Results ##
Parameter <- c(ParamNut,ParamYSI)
Cor <-
c(TDNcor$estimate,TDPcor$estimate,NO3cor$estimate,Chlcor$estimate,D

```

```

Oconccor$estimate,DOsatcor$estimate,pHcor$estimate,Salcor$estimate,
SpCcor$estimate,Tempcor$estimate,Turbcor$estimate)
Pval <-
c(TDNcor$p.value,TDPcor$p.value,NO3cor$p.value,Chlcor$p.value,DOcon
ccor$p.value,DOsatcor$p.value,pHcor$p.value,Salcor$p.value,SpCcor$p
.value,Tempcor$p.value,Turbcor$p.value)
AgatCorResults <-data.frame(Parameter,"R"=Cor,"P"=Pval)

#Export Results to Text File in Working Directory
write.csv(AgatCorResults,"AgatBotSurCorResults.csv")

```

Appendix B. Tests for Seasonality

Table B1. Summary of wet/dry seasonality tests using surface and bottom data lumped and surface data only in marine waters of Kaloko-Honokōhau National Historical Park.

Parameter	Surface and bottom data lumped within a site				Surface data only			
	R ²	main(p)	Time(p)	Wet(p)	R ²	main(p)	Time(p)	Wet(p)
TDN	0.05	0.46	0.41	0.31	0.01	0.92	0.97	0.69
TDP	0.09	0.24	0.13	0.54	0.15	0.31	0.19	0.58
NO ₃ ⁻ + NO ₂ ⁻	0.09	0.24	0.63	0.09	0.24	0.15	0.90	0.05
Chlorophyll	0.14	0.10	0.65	*	0.19	0.22	0.91	0.08
Oxygen	0.17	0.07	0.44	*	0.22	0.20	0.21	0.28
pH	0.12	0.15	0.38	0.09	0.17	0.26	0.35	0.19
Salinity	0.26	*	*	0.10	0.22	0.20	0.09	0.49
Temperature	0.67	***	***	***	0.68	***	**	***
Turbidity	0.12	0.17	0.34	0.08	0.13	0.41	0.42	0.24

* (p < 0.05).

** (p < 0.01).

*** (p < 0.001).

**** (p < 0.0001).

Table B2. Summary of quarter seasonality tests using surface and bottom data lumped and surface data only in marine waters of Kaloko-Honokōhau National Historical Park.

Parameter	Surface and bottom data lumped within a site						Surface data only					
	R ²	main(<i>p</i>)	Time(<i>p</i>)	Q1	Q2	Q3	R ²	main(<i>p</i>)	Time(<i>p</i>)	Q1	Q2	Q3
TDN	0.23	0.10	0.97	0.18	*	0.05	0.38	0.19	0.67	0.14	*	0.24
TDP	0.21	0.13	0.07	0.37	*	0.51	0.34	0.25	0.13	0.42	0.08	0.61
NO ₃ ⁻ + NO ₂ ⁻	0.03	0.91	0.88	0.80	0.84	0.52	0.05	0.96	0.80	0.75	0.98	0.65
Chlorophyll	0.20	0.19	0.51	0.22	0.78	0.18	0.30	0.33	0.88	0.21	0.41	0.40
Oxygen	0.15	0.35	0.24	0.82	0.12	0.42	0.33	0.31	0.13	0.50	0.10	0.58
pH	0.24	0.10	0.26	0.27	0.11	0.36	0.35	0.24	0.27	0.68	0.09	0.38
Salinity	0.29	0.05	**	0.49	0.13	0.09	0.41	0.17	*	0.23	0.09	0.15
Temperature	0.74	***	***	***	**	0.80	0.75	**	**	**	*	0.64
Turbidity	0.05	0.86	0.39	0.50	0.50	0.91	0.07	0.93	0.53	0.61	0.59	0.92

* (*p* < 0.05).

** (*p* < 0.01).

*** (*p* < 0.001).

**** (*p* < 0.0001).

Table B3. Summary of wet/dry seasonality tests using surface and bottom data lumped and surface data only in marine waters of Kalaupapa National Historical Park.

Parameter	Surface and bottom data lumped within a site				Surface data only			
	R ²	main(<i>p</i>)	Time(<i>p</i>)	Wet(<i>p</i>)	R ²	main(<i>p</i>)	Time(<i>p</i>)	Wet(<i>p</i>)
TDN	0.62	***	***	0.52	0.61	*	**	0.68
TDP	0.18	0.13	0.12	0.60	0.24	0.30	0.24	0.67
NO ₃ ⁻ + NO ₂ ⁻	0.28	*	0.70	*	0.30	0.21	0.67	0.16
Chlorophyll	0.30	*	*	0.90	0.43	0.11	0.18	0.38
Oxygen	0.19	0.08	0.23	*	0.12	0.52	0.57	0.26
pH	0.14	0.16	0.13	0.73	0.05	0.76	0.88	0.60
Salinity	0.21	0.06	0.05	0.76	0.20	0.34	0.24	0.93
Temperature	0.18	0.09	0.41	0.15	0.27	0.20	0.29	0.45
Turbidity	0.05	0.56	0.33	0.39	0.01	0.96	0.81	0.81

* (*p* < 0.05).

** (*p* < 0.01).

*** (*p* < 0.001).

**** (*p* < 0.0001).

Table B4. Summary of quarter seasonality tests using surface and bottom data lumped and surface data only in marine waters of Kalaupapa National Historical Park.

Parameter	Surface and bottom data lumped within a site						Surface data only					
	R ²	main(<i>p</i>)	Time(<i>p</i>)	Q1	Q2	Q3	R ²	main(<i>p</i>)	Time(<i>p</i>)	Q1	Q2	Q3
TDN	0.66	***	***	0.11	0.22	0.29	0.64	0.08	*	0.47	0.93	0.80
TDP	0.26	0.20	0.11	0.96	0.89	0.49	0.31	0.57	0.27	0.97	0.98	0.65
NO ₃ ⁻ + NO ₂ ⁻	0.20	0.33	0.40	0.62	0.32	0.14	0.25	0.68	0.52	0.76	0.61	0.37
Chlorophyll	0.32	0.10	*	0.49	0.71	0.89	0.62	0.16	0.17	0.35	0.94	0.55
Oxygen	0.20	0.27	0.28	0.35	0.06	*	0.17	0.80	0.60	0.44	0.34	0.24
pH	0.28	0.11	0.15	0.32	0.29	0.72	0.23	0.67	0.97	0.61	0.39	0.57
Salinity	0.24	0.17	*	0.88	0.56	0.43	0.25	0.63	0.14	0.98	0.64	0.53
Temperature	0.71	***	**	*	***	0.92	0.78	*	*	0.06	*	0.59
Turbidity	0.08	0.81	0.47	0.48	0.35	0.60	0.07	0.93	0.53	0.61	0.59	0.92

* (*p* < 0.05).

** (*p* < 0.01).

*** (*p* < 0.001).

**** (*p* < 0.0001).

Table B5. Summary of wet/dry seasonality tests using surface and bottom data lumped and surface data only in marine waters of War in the Pacific National Historical Park, Asan marine unit.

Parameter	Surface and bottom data lumped within a site				Surface data only			
	R ²	main(<i>p</i>)	Time(<i>p</i>)	Wet(<i>p</i>)	R ²	main(<i>p</i>)	Time(<i>p</i>)	Wet(<i>p</i>)
TDN	0.77	**	**	0.68	0.73	****	****	0.87
TDP	0.25	0.37	0.18	0.75	0.15	0.25	0.10	0.69
NO ₃ ⁻ + NO ₂ ⁻	0.11	0.67	0.56	0.49	0.13	0.31	0.15	0.68
Chlorophyll	0.95	**	*	**	0.81	****	*	****
Oxygen	0.37	0.31	0.15	0.62	0.18	0.23	0.59	0.11
pH	0.11	0.75	0.53	0.76	0.23	0.14	0.05	0.78
Salinity	0.45	0.23	0.35	0.17	0.10	0.45	0.25	0.65
Temperature	0.79	*	0.34	**	0.43	*	*	*
Turbidity	0.11	0.80	0.90	0.58	0.39	*	0.07	*

* (*p* < 0.05).

** (*p* < 0.01).

*** (*p* < 0.001).

**** (*p* < 0.0001).

Table B6. Summary of quarter seasonality tests using surface and bottom data lumped and surface data only in marine waters of War in the Pacific National Historical Park, Asan marine unit.

Parameter	Surface and bottom data lumped within a site						Surface data only					
	R ²	main(<i>p</i>)	Time(<i>p</i>)	Q1	Q2	Q3	R ²	main(<i>p</i>)	Time(<i>p</i>)	Q1	Q2	Q3
TDN	0.79	****	****	0.76	0.83	0.20	0.80	0.06	0.01	0.80	0.78	0.84
TDP	0.25	0.34	0.19	0.97	0.62	0.73	0.40	0.56	0.30	0.98	0.69	0.78
NO ₃ ⁻ + NO ₂ ⁻	0.24	0.35	0.25	0.42	0.44	0.17	0.47	0.45	0.82	0.92	0.62	0.21
Chlorophyll	0.85	****	0.17	****	0.52	0.69	1.00	**	*	**	0.26	0.05
Oxygen	0.38	0.15	*	0.35	0.49	0.14	0.56	0.54	0.18	0.71	0.67	0.36
pH	0.44	0.09	0.66	0.09	*	*	0.52	0.59	0.99	0.41	0.27	0.20
Salinity	0.54	*	0.29	0.57	0.07	0.21	0.58	0.52	0.86	0.76	0.36	0.39
Temperature	0.70	**	0.96	**	0.87	0.37	0.73	0.30	0.97	0.18	0.95	0.54
Turbidity	0.11	0.85	0.71	0.34	0.53	0.37	0.31	0.90	0.72	0.51	0.63	0.52

* (*p* < 0.05).

** (*p* < 0.01).

*** (*p* < 0.001).

**** (*p* < 0.0001).

Table B7. Summary of wet/dry seasonality tests using surface and bottom data lumped and surface data only in marine waters of War in the Pacific National Historical Park, Agat marine unit.

Parameter	Surface and bottom data lumped within a site				Surface data only			
	R ²	main(<i>p</i>)	Time(<i>p</i>)	Wet(<i>p</i>)	R ²	main(<i>p</i>)	Time(<i>p</i>)	Wet(<i>p</i>)
TDN	0.35	*	*	0.91	0.28	0.32	0.19	0.68
TDP	0.04	0.71	0.90	0.45	0.06	0.81	0.81	0.60
NO ₃ ⁻ + NO ₂ ⁻	****	0.98	0.84	0.95	0.05	0.87	1.00	0.63
Chlorophyll	0.40	*	0.05	*	0.91	**	0.07	**
Oxygen	0.14	0.28	0.58	0.15	0.19	0.53	0.73	0.32
pH	0.16	0.23	0.18	0.34	0.15	0.61	0.48	0.56
Salinity	0.70	****	****	*	0.72	*	*	0.07
Temperature	0.78	****	0.10	****	0.79	**	0.28	**
Turbidity	*	0.76	0.58	0.59	0.60	0.10	0.05	0.27

* (*p* < 0.05).

** (*p* < 0.01).

*** (*p* < 0.001).

**** (*p* < 0.0001).

Table B8. Summary of quarter seasonality tests using surface and bottom data lumped and surface data only in marine waters of War in the Pacific National Historical Park, Agat marine unit.

Parameter	Surface and bottom data lumped within a site						Surface data only					
	R ²	main(<i>p</i>)	Time(<i>p</i>)	Q1	Q2	Q3	R ²	main(<i>p</i>)	Time(<i>p</i>)	Q1	Q2	Q3
TDN	0.48	*	*	0.79	0.84	0.35	0.46	0.47	0.16	0.78	0.87	0.49
TDP	0.09	0.84	0.58	0.99	0.61	0.38	0.14	0.92	0.62	0.99	0.73	0.54
NO ₃ ⁻ + NO ₂ ⁻	0.06	0.93	0.73	0.96	0.96	0.58	0.25	0.84	0.79	0.43	0.67	0.95
Chlorophyll	0.42	0.11	0.18	0.09	0.78	0.98	0.99	****	0.37	****	0.12	0.22
Oxygen	0.81	****	*	****	****	****	0.88	*	0.11	*	*	*
pH	0.45	0.05	0.65	0.19	0.08	*	0.54	0.45	0.89	0.50	0.30	0.14
Salinity	0.66	****	****	0.28	0.37	0.33	0.68	0.24	0.23	0.47	0.71	0.57
Temperature	0.69	****	0.99	*	0.98	0.15	0.72	0.20	0.84	0.19	0.77	0.32
Turbidity	0.21	0.52	0.54	0.46	0.85	0.26	0.83	0.16	0.13	0.11	0.33	0.17

* (*p* < 0.05).

** (*p* < 0.01).

*** (*p* < 0.001).

**** (*p* < 0.0001).

Table B9. Summary of wet/dry seasonality tests using surface and bottom data lumped and surface data only in marine waters of National Park of American Samoa, Tutuila.

Parameter	Surface and bottom data lumped within a site				Surface data only			
	R ²	main(<i>p</i>)	Time(<i>p</i>)	Wet(<i>p</i>)	R ²	main(<i>p</i>)	Time(<i>p</i>)	Wet(<i>p</i>)
TDN	0.05	0.46	0.41	0.31	0.01	0.92	0.97	0.69
TDP	0.09	0.24	0.13	0.54	0.15	0.31	0.19	0.58
NO ₃ ⁻ + NO ₂ ⁻	0.09	0.24	0.63	0.09	0.24	0.15	0.90	0.05
Chlorophyll	0.14	0.10	0.65	*	0.19	0.22	0.91	0.08
Oxygen	0.17	0.07	0.44	*	0.22	0.20	0.21	0.28
pH	0.12	0.15	0.38	0.09	0.17	0.26	0.35	0.19
Salinity	0.26	*	*	0.10	0.22	0.20	0.09	0.49
Temperature	0.67	***	***	***	0.68	***	**	***
Turbidity	0.12	0.17	0.34	0.08	0.13	0.41	0.42	0.24

* (*p* < 0.05).

** (*p* < 0.01).

*** (*p* < 0.001).

**** (*p* < 0.0001).

Table B10. Summary of quarter seasonality tests using surface and bottom data lumped and surface data only in marine waters of National Park of American Samoa, Tutuila.

Parameter	Surface and bottom data lumped within a site						Surface data only					
	R ²	main(<i>p</i>)	Time(<i>p</i>)	Q1	Q2	Q3	R ²	main(<i>p</i>)	Time(<i>p</i>)	Q1	Q2	Q3
TDN	0.23	0.10	0.97	0.18	*	0.05	0.38	0.19	0.67	0.14	*	0.24
TDP	0.21	0.13	0.07	0.37	*	0.51	0.34	0.25	0.13	0.42	0.08	0.61
NO ₃ ⁻ + NO ₂ ⁻	0.03	0.91	0.88	0.80	0.84	0.52	0.05	0.96	0.80	0.75	0.98	0.65
Chlorophyll	0.20	0.19	0.51	0.22	0.78	0.18	0.30	0.33	0.88	0.21	0.41	0.40
Oxygen	0.15	0.35	0.24	0.82	0.12	0.42	0.33	0.31	0.13	0.50	0.10	0.58
pH	0.24	0.10	0.26	0.27	0.11	0.36	0.35	0.24	0.27	0.68	0.09	0.38
Salinity	0.29	0.05	**	0.49	0.13	0.09	0.41	0.17	*	0.23	0.09	0.15
Temperature	0.74	***	***	***	**	0.80	0.75	**	**	**	*	0.64
Turbidity	0.05	0.86	0.39	0.50	0.50	0.91	0.07	0.93	0.53	0.61	0.59	0.92

* (*p* < 0.05).

** (*p* < 0.01).

*** (*p* < 0.001).

**** (*p* < 0.0001).

Table B11. Summary of wet/dry seasonality tests using surface and bottom data lumped and surface data only in marine waters of National Park of American Samoa, Ofu.

Parameter	Surface and bottom data lumped within a site				Surface data only			
	R ²	main(<i>p</i>)	Time(<i>p</i>)	Wet(<i>p</i>)	R ²	main(<i>p</i>)	Time(<i>p</i>)	Wet(<i>p</i>)
TDN	0.05	0.46	0.41	0.31	0.01	0.92	0.97	0.69
TDP	0.09	0.24	0.13	0.54	0.15	0.31	0.19	0.58
NO ₃ ⁻ + NO ₂ ⁻	0.09	0.24	0.63	0.09	0.24	0.15	0.90	0.05
Chlorophyll	0.14	0.10	0.65	*	0.19	0.22	0.91	0.08
Oxygen	0.17	0.07	0.44	*	0.22	0.20	0.21	0.28
pH	0.12	0.15	0.38	0.09	0.17	0.26	0.35	0.19
Salinity	0.26	*	*	0.10	0.22	0.20	0.09	0.49
Temperature	0.67	***	***	***	0.68	***	**	***
Turbidity	0.12	0.17	0.34	0.08	0.13	0.41	0.42	0.24

* (*p* < 0.05).

** (*p* < 0.01).

*** (*p* < 0.001).

**** (*p* < 0.0001).

Table B12. Summary of quarter seasonality tests using surface and bottom data lumped and surface data only in marine waters of National Historical Park of American Samoa, Ofu.

Parameter	Surface and bottom data lumped within a site						Surface data only					
	R ²	main(<i>p</i>)	Time(<i>p</i>)	Q1	Q2	Q3	R ²	main(<i>p</i>)	Time(<i>p</i>)	Q1	Q2	Q3
TDN	0.23	0.10	0.97	0.18	*	0.05	0.38	0.19	0.67	0.14	*	0.24
TDP	0.21	0.13	0.07	0.37	*	0.51	0.34	0.25	0.13	0.42	0.08	0.61
NO ₃ ⁻ + NO ₂ ⁻	0.03	0.91	0.88	0.80	0.84	0.52	0.05	0.96	0.80	0.75	0.98	0.65
Chlorophyll	0.20	0.19	0.51	0.22	0.78	0.18	0.30	0.33	0.88	0.21	0.41	0.40
Oxygen	0.15	0.35	0.24	0.82	0.12	0.42	0.33	0.31	0.13	0.50	0.10	0.58
pH	0.24	0.10	0.26	0.27	0.11	0.36	0.35	0.24	0.27	0.68	0.09	0.38
Salinity	0.29	0.05	**	0.49	0.13	0.09	0.41	0.17	*	0.23	0.09	0.15
Temperature	0.74	***	***	***	**	0.80	0.75	**	**	**	*	0.64
Turbidity	0.05	0.86	0.39	0.50	0.50	0.91	0.07	0.93	0.53	0.61	0.59	0.92

* (*p* < 0.05).

** (*p* < 0.01).

*** (*p* < 0.001).

**** (*p* < 0.0001).

Appendix C. Results of Statistical Trend Tests

Table C1. Summary of trend tests in marine waters of National Park of American Samoa, Tutuila, 2008–2015.

Parameter	Seasonality	Depth/Site	Censored (%)	M-K(<i>p</i>)	Seasonal M-K	Trend
NO ₃ ⁻ + NO ₂ ⁻	N	Surface	54	–	–	None
	N	Bottom	39	0.57	–	None
TDP	N	Surface	12	0.18	–	None
	N	Bottom	86	–	1.0	None
TDN	N	Surface	84	–	–	None
	N	Bottom	8	–	–	None
Chlorophyll	N	Surface	46	0.81	–	None
	N	Bottom	43	0.80	–	None
Turbidity	N	Surface	100	–	–	None
	N	Bottom	97	–	–	None
Oxygen	N	Surface	0	0.31	–	None
	N	Bottom	0	0.46	–	None
pH	N	Surface	0	0.31	–	None
	N	Bottom	0	0.46	–	None
Salinity	N	Surface	0	0.73	–	None
	N	Bottom	0	0.22	–	None
Temperature	Y	Surface	0	0.73	–	None
	Y	Bottom	0	0.80	–	None

* (*p* < 0.05).

** (*p* < 0.01).

*** (*p* < 0.001).

**** (*p* < 0.0001).

M-K = Mann-Kendall test.

Y = Yes, N = No.

Table C2. Summary of trend tests in marine waters of National Park of American Samoa, Ofu, 2008–2015.

Parameter	Seasonality	Depth/Site	Censored (%)	M-K(<i>p</i>)	Trend
NO ₃ ⁻ + NO ₂ ⁻	N	Surface	0	0.28	None
TDP	N	Surface	95	–	None
TDN	N	Surface	3	0.54	None
Chlorophyll	N	Surface	66	–	None
Turbidity	N	Surface	50	–	None
Oxygen	N	Surface	0	0.92	None
pH	N	Surface	0	0.32	None
Salinity	N	Surface	0	*	Decreasing
Temperature	Y	Surface	0	0.28	None

* (*p* < 0.05).

** (*p* < 0.01).

*** (*p* < 0.001).

**** (*p* < 0.0001).

M-K = Mann-Kendall test.

Y = Yes, N = No.

Table C3. Summary of trend tests in marine waters of Kaloko-Honokōhau National Historical Park, 2008–2015.

Parameter	Seasonality	Depth/Site	Censored (%)	M-K(<i>p</i>)	Time(<i>p</i>)	Depth(<i>p</i>)	Time: Depth(<i>p</i>)	Wet(<i>p</i>)	Quarter(<i>p</i>)	Trend
NO ₃ ⁻ + NO ₂ ⁻	N	Surface	8	1.00	–	–	–	–	–	None
	N	Bottom	35	0.53	–	–	–	–	–	None
TDP	N	Surface	88	–	–	–	–	–	–	None
	N	Bottom	98	–	–	–	–	–	–	None
TDN	N	Surface	7	0.59	–	–	–	–	–	None
	N	Bottom	14	0.65	–	–	–	–	–	None
Chlorophyll	N	Surface	45	0.77	–	–	–	–	–	None
	N	Bottom	54	–	–	–	–	–	–	None
Turbidity	N	Surface	74	–	–	–	–	–	–	None
	N	Bottom	75	–	–	–	–	–	–	None
Oxygen	N	Fixed Surface	0	–	0.80	–	–	–	–	None
	N	Fixed Bottom	0	–	0.80	–	–	–	–	None
	N	All	0	–	0.75	0.09	0.23	–	–	None
pH	N	Fixed Surface	0	–	0.30	–	–	–	–	None
	N	Fixed Bottom	0	–	0.30	–	–	–	–	None
	N	All	0	–	0.21	0.85	0.98	–	–	None

* (*p* < 0.05).

** (*p* < 0.01).

*** (*p* < 0.001).

**** (*p* < 0.0001).

M-K = Mann-Kendall test.

Y = Yes, N = No.

Table C3 (continued). Summary of trend tests in marine waters of Kaloko-Honokōhau National Historical Park, 2008–2015.

Parameter	Seasonality	Depth/Site	Censored (%)	M-K(<i>p</i>)	Time(<i>p</i>)	Depth(<i>p</i>)	Time: Depth(<i>p</i>)	Wet(<i>p</i>)	Quarter(<i>p</i>)	Trend
Salinity	N	Fixed Surface	0	—	0.05	—	—	—	—	Decreasing
	N	Fixed Bottom	0	—	0.05	—	—	—	—	Decreasing
	N	All	0	—	*	****	0.07	—	—	Decreasing
Temperature	Y	Fixed Surface	0	—	*	—	—	****	****	Increasing
	Y	Fixed Bottom	0	—	0.05	—	—	****	****	Increasing
	Y	All	0	—	0.05	0.16	0.25	****	****	Increasing

* ($p < 0.05$).

** ($p < 0.01$).

*** ($p < 0.001$).

**** ($p < 0.0001$).

M-K = Mann-Kendall test.

Y = Yes, N = No.

Table C4. Summary of trend tests in marine waters of Kalaupapa National Historical Park, 2008–2015.

Parameter/	Seasonality	Depth/Site	Censored (%)	M-K(<i>p</i>)	Time (<i>p</i>)	Depth (<i>p</i>)	Time: Depth (<i>p</i>)	Wet (<i>p</i>)	Quarter (<i>p</i>)	Trend
NO ₃ ⁻ + NO ₂ ⁻	N	Surface	0	0.30	–	–	–	–	–	None
	N	Bottom	48	0.33	–	–	–	–	–	None
TDP	N	Surface	95	–	–	–	–	–	–	None
	N	Bottom	96	–	–	–	–	–	–	None
TDN	N	Surface	3	0.11	–	–	–	–	–	Decreasing
	N	Bottom	21	0.03	–	–	–	–	–	Decreasing
Chlorophyll	N	Surface	58	–	–	–	–	–	–	None
	N	Bottom	77	–	–	–	–	–	–	None
Turbidity	N	Surface	98	–	–	–	–	–	–	None
	N	Bottom	99	–	–	–	–	–	–	None
Oxygen	N	Fixed Surface	0	–	0.31	–	–	–	–	None
	N	Fixed Bottom	0	–	0.61	–	–	–	–	None
	N	All	0	–	0.42	0.35	0.45	–	–	None
pH	N	Fixed Surface	0	–	0.77	–	–	–	–	None
	N	Fixed Bottom	0	–	0.32	–	–	–	–	None
	N	All	0	–	**	*	****	–	–	None

* (*p* < 0.05).

** (*p* < 0.01).

*** (*p* < 0.001).

**** (*p* < 0.0001).

M-K = Mann-Kendall test.

Y = Yes, N = No.

Table C4 (continued). Summary of trend tests in marine waters of Kalaupapa National Historical Park, 2008–2015.

Parameter/	Seasonality	Depth/Site	Censored (%)	M-K(<i>p</i>)	Time (<i>p</i>)	Depth (<i>p</i>)	Time: Depth (<i>p</i>)	Wet (<i>p</i>)	Quarter (<i>p</i>)	Trend
Salinity	N	Fixed Surface	0	–	0.16	–	–	–	–	Decreasing
	N	Fixed Bottom	0	–	0.19	–	–	–	–	Decreasing
	N	All	0	–	****	0.85	0.58	–	–	Decreasing
Temperature	Y	Fixed Surface	0	–	*	–	–	–	–	Increasing
	Y	Fixed Bottom	0	–	****	–	–	–	–	Increasing
	Y	All	0	–	****	0.61	****	–	–	Increasing

* ($p < 0.05$).

** ($p < 0.01$).

*** ($p < 0.001$).

**** ($p < 0.0001$).

M-K = Mann-Kendall test.

Y = Yes, N = No.

Table C5. Summary of trend tests in marine waters of War in the Pacific NHP, Asan Marine Unit, 2008–2015.

Parameter/	Seasonality	Depth/Site	Censored (%)	M-K(<i>p</i>)	Time (<i>p</i>)	Depth (<i>p</i>)	Time: Depth (<i>p</i>)	Wet (<i>p</i>)	Quarter (<i>p</i>)	Trend
NO ₃ ⁻ + NO ₂ ⁻	N	Surface	36	0.15	–	–	–	–	–	None
	N	Bottom	38	0.47	–	–	–	–	–	None
TDP	N	Surface	94	–	–	–	–	–	–	None
	N	Bottom	97	–	–	–	–	–	–	None
TDN	N	Surface	17	0.09	–	–	–	–	–	None
	N	Bottom	19	0.07	–	–	–	–	–	None
Chlorophyll	N	Surface	56	–	–	–	–	–	–	None
	N	Bottom	62	–	–	–	–	–	–	None
Turbidity	N	Surface	90	–	–	–	–	–	–	None
	N	Bottom	95	–	–	–	–	–	–	None
Oxygen	N	Fixed Surface	0	–	0.18	–	–	–	–	None
	N	Fixed Bottom	0	–	0.31	–	–	–	–	None
	N	All	0	–	0.46	0.07	0.18	–	–	None
pH	N	Fixed Surface	0	–	0.43	–	–	–	–	None
	N	Fixed Bottom	0	–	0.35	–	–	–	–	None
	N	All	0	–	0.33	0.87	0.46	–	–	None

* (*p* < 0.05).

** (*p* < 0.01).

*** (*p* < 0.001).

**** (*p* < 0.0001).

M-K = Mann-Kendall test.

Y = Yes, N = No.

Table C5 (continued). Summary of trend tests in marine waters of War in the Pacific NHP, Asan Marine Unit, 2008–2015.

Parameter/	Seasonality	Depth/Site	Censored (%)	M-K(<i>p</i>)	Time (<i>p</i>)	Depth (<i>p</i>)	Time: Depth (<i>p</i>)	Wet (<i>p</i>)	Quarter (<i>p</i>)	Trend
Salinity	N	Fixed Surface	0	–	0.19	–	–	–	–	Decreasing
	N	Fixed Bottom	0	–	0.06	–	–	–	–	Decreasing
	N	All	0	–	**	0.18	0.64	–	–	Decreasing
Temperature	Y	Fixed Surface	0	–	0.30	–	–	****	0.06	None
	Y	Fixed Bottom	0	–	0.45	–	–	****	****	None
	Y	All	0	–	0.59	0.19	0.06	****	****	None

* ($p < 0.05$).

** ($p < 0.01$).

*** ($p < 0.001$).

**** ($p < 0.0001$).

M-K = Mann-Kendall test.

Y = Yes, N = No.

Table C6. Summary of trend tests in marine waters of War in the Pacific NHP, Agat Marine Unit, 2008–2015.

Parameter	Seasonality	Depth/Site	Censored (%)	M-K (p)	Seasonal M-K	Time (p)	Depth (p)	Time: Depth (p)	Wet (p)	Quarter (p)	Trend
NO ₃ ⁻ + NO ₂ ⁻	N	Surface	33	0.67	–	–	–	–	–	–	None
	N	Bottom	40	0.92	–	–	–	–	–	–	None
TDP	N	Surface	95	–	–	–	–	–	–	–	None
	N	Bottom	97	–	–	–	–	–	–	–	None
TDN	N	Surface	19	0.47	–	–	–	–	–	–	None
	N	Bottom	19	0.07	–	–	–	–	–	–	None
Chlorophyll	N	Surface	60	–	–	–	–	–	–	–	Decreasing
	N	Bottom	43	–	*	–	–	–	–	–	Decreasing
Turbidity	N	Surface	95	–	–	–	–	–	–	–	None
	N	Bottom	96	–	–	–	–	–	–	–	None
Oxygen	N	Fixed Surface	0	–	–	0.61	–	–	–	–	None
	N	Fixed Bottom	0	–	–	0.61	–	–	–	–	None
	N	All	0	–	–	0.42	0.82	0.64	–	–	None

* (p < 0.05).

** (p < 0.01).

*** (p < 0.001).

**** (p < 0.0001).

M-K = Mann-Kendall test.

Y = Yes, N = No.

Table C6 (continued). Summary of trend tests in marine waters of War in the Pacific NHP, Agat Marine Unit, 2008–2015.

Parameter	Seasonality	Depth/Site	Censored (%)	M-K (p)	Seasonal M-K	Time (p)	Depth (p)	Time: Depth (p)	Wet (p)	Quarter (p)	Trend
pH	N	Fixed Surface	0	—	—	0.36	—	—	—	—	None
	N	Fixed Bottom	0	—	—	0.27	—	—	—	—	None
	N	All	0	—	—	0.15	0.72	0.82	—	—	None
Salinity	N	Fixed Surface	0	—	—	0.28	—	—	—	—	None
	N	Fixed Bottom	0	—	—	0.13	—	—	—	—	None
	N	All	0	—	—	0.12	0.12	0.96	—	—	None
Temperature	Y	Fixed Surface	0	—	—	0.36	—	—	****	****	None
	Y	Fixed Bottom	0	—	—	0.36	—	—	****	****	None
	Y	All	0	—	—	0.61	**	0.94	****	****	None

* (p < 0.05).

** (p < 0.01).

*** (p < 0.001).

**** (p < 0.0001).

M-K = Mann-Kendall test.

Y = Yes, N = No.

Appendix D. Ranges of water quality parameters

Data collected during unusual conditions were not included in range summary tables; data removed included pH and turbidity at both surface and bottom sites at Kaloko-Honokōhau NHP during 2010 Q4 and 2011 Q1 due to the likely presence of an algal bloom, and a small number of measurements at War in the Pacific National Park that were collected close to river mouths likely influenced by runoff. However, these values are included in Figures 6 and 7 to provide an understanding of how water quality parameters range under normal and episodic events.

Table D1. Ranges of water quality parameters at PACN parks 2008–2015.

Location	Statistic	NO ⁻³ + NO ⁻² (µg/L)	NO ⁻³ + NO ⁻² (µg/L)	TDN (mg/L)	TDN (mg/L)	TDP (µg/L)	TDP (µg/L	TN (mg/L)	TN (mg/L)	TP (mg/L)	TP (mg/L)	Chl (µg/L)	Chl (µg/L)	O2 Sat. (%)	O2 Sat. (%)	pH Surface	pH Bottom	Salinity (ppt)	Salinity (ppt)	Temp (°C)	Temp (°C)	Turbidity (FNU)	Turbidity (FNU)
		Surface	Bottom	Surface	Bottom)	Surface	Bottom)	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom			Surface	Bottom	Surface	Bottom	Surface	Bottom
KAHO: North of Honokohau Small Boat Harbor	n	107	107	107	107	107	107	14	14	14	14	170	192	194	201	172	173	200	201	202	203	161	162
	Maximum	40.30	11.40	0.19	0.15	22.30	17.33	0.17	0.15	0.02	0.05	13.68	8.36	123.29	113.05	8.32	8.31	36.16	36.20	29.03	28.50	2.94	1.91
	3rd Quartile	13.00	3.33	0.11	0.10	15.00	15.00	0.10	0.08	0.02	0.02	0.47	0.26	106.79	104.25	8.16	8.16	35.33	35.59	26.92	26.71	0.10	0.10
	Mean	9.66	2.57	0.10	0.09	15.12	15.02	0.09	0.08	0.02	0.02	0.70	0.38	104.28	102.71	8.09	8.10	35.14	35.38	26.33	26.17	0.20	0.18
	Median	7.00	1.60	0.10	0.09	15.00	15.00	0.08	0.07	0.02	0.02	0.18	0.10	103.94	102.29	8.11	8.12	35.17	35.34	26.48	26.21	0.10	0.10
	1st Quartile	2.33	1.00	0.08	0.07	15.00	15.00	0.07	0.07	0.02	0.02	0.10	0.10	100.99	100.90	8.01	8.02	34.92	35.19	25.53	25.48	0.10	0.10
	Minimum	1.00	1.00	0.07	0.07	15.00	15.00	0.07	0.07	0.02	0.02	0.00	0.00	89.93	94.81	7.94	7.92	33.56	34.69	23.47	23.28	0.10	0.10
KAHO: Honokohau Small Boat Harbor plume- affected area	n	21	21	21	21	21	21	2	2	2	2	46	45	49	50	42	42	50	50	50	50	39	39
	Maximum	165.97	14.33	0.26	0.16	40.05	16.40	0.11	0.10	0.02	0.02	5.48	9.06	127.78	107.07	8.30	8.29	35.98	36.10	28.81	28.33	2.16	2.05
	3rd Quartile	70.67	6.33	0.17	0.10	17.33	15.00	0.10	0.09	0.02	0.02	0.58	0.26	106.31	104.19	8.16	8.17	35.24	35.57	26.87	26.63	0.10	0.10
	Mean	52.04	4.90	0.15	0.09	17.38	15.07	0.09	0.09	0.02	0.02	0.72	0.47	104.38	102.96	8.11	8.11	34.86	35.38	26.18	26.15	0.27	0.26
	Median	39.00	3.33	0.15	0.08	15.33	15.00	0.09	0.09	0.02	0.02	0.25	0.10	103.32	102.73	8.13	8.14	35.06	35.33	26.15	26.07	0.10	0.10
	1st Quartile	25.03	1.33	0.11	0.08	15.00	15.00	0.08	0.08	0.02	0.02	0.10	0.10	101.70	101.85	8.01	8.03	34.50	35.20	25.49	25.43	0.10	0.10
	Minimum	5.00	1.00	0.08	0.07	15.00	15.00	0.07	0.07	0.02	0.02	0.00	0.00	96.48	98.72	7.96	7.98	33.05	34.69	23.39	23.77	0.10	0.10
KALA	n	95	92	95	92	95	92	24	22	24	22	145	185	208	227	197	215	222	241	229	246	177	198
	Maximum	12.47	4.77	0.19	0.18	23.33	23.67	0.11	0.12	0.02	0.02	4.56	9.64	118.29	112.00	8.32	8.36	37.30	37.31	27.10	26.89	2.83	2.97
	3rd Quartile	3.07	2.36	0.11	0.09	15.00	15.00	0.07	0.07	0.02	0.02	0.36	0.10	105.66	104.97	8.16	8.16	35.57	35.60	25.55	25.52	0.10	0.10
	Mean	2.33	1.80	0.09	0.09	15.27	15.18	0.08	0.07	0.02	0.02	0.41	0.27	104.06	103.16	8.08	8.07	35.11	35.16	25.16	25.07	0.12	0.11
	Median	2.00	1.33	0.09	0.08	15.00	15.00	0.07	0.07	0.02	0.02	0.10	0.10	103.64	102.92	8.10	8.10	35.05	35.33	25.06	25.04	0.10	0.10
	1st Quartile	1.00	1.00	0.08	0.07	15.00	15.00	0.07	0.07	0.02	0.02	0.10	0.10	101.93	101.28	7.97	7.97	34.68	34.70	24.68	24.65	0.10	0.10
	Minimum	1.00	1.00	0.07	0.07	15.00	15.00	0.07	0.05	0.02	0.02	0.01	0.00	95.30	94.88	7.75	7.56	33.14	33.33	23.38	23.30	0.10	0.10
WAPA: Asan Marine Unit	n	36	36	38	38	38	38	9	10	9	10	49	67	61	76	66	79	66	79	66	79	50	63
	Maximum	13.33	7.67	0.14	0.14	20.67	15.33	0.07	0.08	0.02	0.02	3.84	3.04	129.24	108.65	8.32	8.30	36.36	36.36	30.46	29.98	3.33	0.40
	3rd Quartile	3.42	3.23	0.10	0.10	15.00	15.00	0.07	0.07	0.02	0.02	0.19	0.20	106.09	103.66	8.18	8.16	35.64	35.67	29.79	29.34	0.10	0.10
	Mean	2.71	2.26	0.09	0.09	15.16	15.01	0.07	0.07	0.02	0.02	0.40	0.33	104.21	101.30	8.11	8.10	34.60	34.78	29.11	28.95	0.22	0.11
	Median	1.87	1.55	0.09	0.08	15.00	15.00	0.07	0.07	0.02	0.02	0.10	0.10	102.80	101.14	8.11	8.13	34.79	34.91	29.04	29.00	0.10	0.10
	1st Quartile	1.00	1.00	0.07	0.07	15.00	15.00	0.07	0.07	0.02	0.02	0.10	0.10	100.52	99.63	8.06	8.06	34.19	34.24	28.73	28.62	0.10	0.10
	Minimum	1.00	1.00	0.07	0.07	15.00	15.00	0.07	0.07	0.02	0.02	0.00	0.02	96.64	90.11	7.94	7.88	31.51	32.92	27.23	27.23	0.10	0.10
WAPA: Agat	n	33	30	36	34	37	34	8	8	8	8	50	74	72	87	78	91	78	91	78	91	62	77
	Maximum	10.67	7.67	0.13	0.17	25.00	16.00	0.10	0.07	0.06	0.02	6.96	6.63	130.23	108.38	8.27	8.26	36.38	36.38	31.86	33.29	2.49	5.55

Location	Statistic	NO ⁻³ + NO ⁻² (µg/L)	NO ⁻³ + NO ⁻² (µg/L)	TDN (mg/L)	TDN (mg/L)	TDP (µg/L)	TDP (µg/L	TN (mg/L)	TN (mg/L)	TP (mg/L)	TP (mg/L)	Chl (µg/L)	Chl (µg/L)	O2 Sat. (%)	O2 Sat. (%)	pH	pH	Salinity (ppt)	Salinity (ppt)	Temp (°C)	Temp (°C)	Turbidity (FNU)	Turbidity (FNU)
		Surface	Bottom	Surface	Bottom)	Surface	Bottom)	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom			Surface	Bottom	Surface	Bottom	Surface	Bottom
Marine Unit	3rd Quartile	6.00	4.27	0.10	0.11	15.00	15.00	0.07	0.07	0.02	0.02	0.23	0.25	104.89	104.29	8.15	8.17	35.56	35.66	30.04	29.69	0.10	0.10
	Mean	3.41	2.79	0.09	0.09	15.32	15.06	0.07	0.07	0.03	0.02	0.29	0.35	100.33	99.94	8.10	8.10	34.12	34.35	29.39	29.19	0.15	0.20
	Median	2.00	2.00	0.08	0.08	15.00	15.00	0.07	0.07	0.02	0.02	0.10	0.14	100.00	100.48	8.12	8.11	34.56	34.72	29.34	29.17	0.10	0.10
	1st Quartile	1.00	1.00	0.08	0.07	15.00	15.00	0.07	0.07	0.02	0.02	0.10	0.10	97.83	97.67	8.03	8.05	34.14	34.23	28.98	28.82	0.10	0.10
	Minimum	1.00	1.00	0.07	0.07	15.00	15.00	0.07	0.07	0.02	0.02	0.00	0.01	81.39	76.98	7.92	7.92	2.04	2.05	27.27	27.28	0.10	0.10
NPSA: Tutuila	n	47	47	51	51	50	51	–	–	–	–	50	69	56	73	56	73	55	73	56	73	50	67
	Maximum	10.00	21.00	0.43	0.24	21.67	21.33	–	–	–	–	4.58	4.66	132.17	132.46	8.18	8.36	38.55	38.50	30.29	30.11	0.10	2.45
	3rd Quartile	3.75	4.17	0.12	0.12	15.00	15.00	–	–	–	–	0.28	0.22	119.55	124.50	8.15	8.21	37.19	37.11	29.90	29.75	0.10	0.10
	Mean	2.52	3.26	0.12	0.11	15.41	15.39	–	–	–	–	0.36	0.30	112.62	114.12	8.11	8.11	37.14	36.37	29.54	29.40	0.10	0.15
	Median	1.00	2.00	0.10	0.10	15.00	15.00	–	–	–	–	0.14	0.11	114.21	116.49	8.10	8.07	36.93	35.76	29.74	29.62	0.10	0.10
NPSA: Ofu	1st Quartile	1.00	1.00	0.08	0.08	15.00	15.00	–	–	–	–	0.10	0.10	101.60	100.93	8.07	8.03	36.89	35.61	29.40	29.30	0.10	0.10
	Minimum	0.00	0.00	0.07	0.07	15.00	15.00	–	–	–	–	0.01	0.00	97.10	94.68	8.02	7.99	35.45	35.32	28.29	27.74	0.10	0.10
	n	56	–	60	–	60	56	–	–	–	–	29	5	20	2	30	7	32	7	32	7	28	6
	Maximum	30.33	–	0.25	–	16.33	30.33	–	–	–	–	1.39	1.72	160.80	115.86	8.22	8.30	37.06	36.70	31.05	30.49	35.36	0.10
	3rd Quartile	15.84	–	0.12	–	15.00	15.84	–	–	–	–	0.53	0.84	132.57	112.49	8.14	8.21	36.43	35.71	29.72	30.03	11.75	0.10
	Mean	12.13	–	0.11	–	15.04	12.13	–	–	–	–	0.33	0.61	122.82	109.12	8.10	8.18	35.87	35.14	29.09	29.80	9.11	0.10
	Median	10.07	–	0.11	–	15.00	10.07	–	–	–	–	0.10	0.32	123.85	109.12	8.11	8.18	35.87	35.64	29.07	29.75	0.10	0.10
	1st Quartile	7.33	–	0.09	–	15.00	7.33	–	–	–	–	0.10	0.10	106.70	105.75	8.08	8.14	35.66	34.46	28.42	29.50	0.10	0.10
	Minimum	3.17	–	0.07	–	15.00	3.17	–	–	–	–	0.00	0.07	91.90	102.38	7.93	8.13	33.32	33.35	27.47	29.31	0.10	0.10

Appendix E. Data Censoring

Turbidity and TDP data were more than 50% censored at all parks at both depths (Table 11). $\text{NO}_3 + \text{NO}_2$ and chlorophyll data were more than 50% censored at some parks. In every case, censoring of these parameters reflected very low turbidity, nutrient concentrations, and chlorophyll concentrations.

Table E1. Rate of data censorship in selected parameters within marine areas of PACN national parks.

Park	Parameter	% Surface data censored	% Bottom data censored
KAHO	$\text{NO}_3^- + \text{NO}_2^-$	8	35
	TDN	7	14
	TDP	88	98
	Chlorophyll	45	54
	Turbidity	74	75
KALA	$\text{NO}_3^- + \text{NO}_2^-$	36	48
	TDN	18	21
	TDP	91	96
	Chlorophyll	58	77
	Turbidity	98	99
WAPA – Asan	$\text{NO}_3^- + \text{NO}_2^-$	36	10
	TDN	17	11
	TDP	94	90
	Chlorophyll	56	62
	Turbidity	90	95
WAPA – Agat	$\text{NO}_3^- + \text{NO}_2^-$	33	38
	TDN	19	19
	TDP	95	97
	Chlorophyll	60	43
	Turbidity	95	96
NPSA – Ofu	$\text{NO}_3^- + \text{NO}_2^-$	0	–
	TDN	3	–
	TDP	95	–
	Chlorophyll	66	–
	Turbidity	50	–

Park	Parameter	% Surface data censored	% Bottom data censored
NPSA – Tutuila	$\text{NO}_3^- + \text{NO}_2^-$	54	39
	TDN	12	8
	TDP	84	86
	Chlorophyll	46	43
	Turbidity	100	97

Appendix F. Distribution of dissolved nutrient fractions

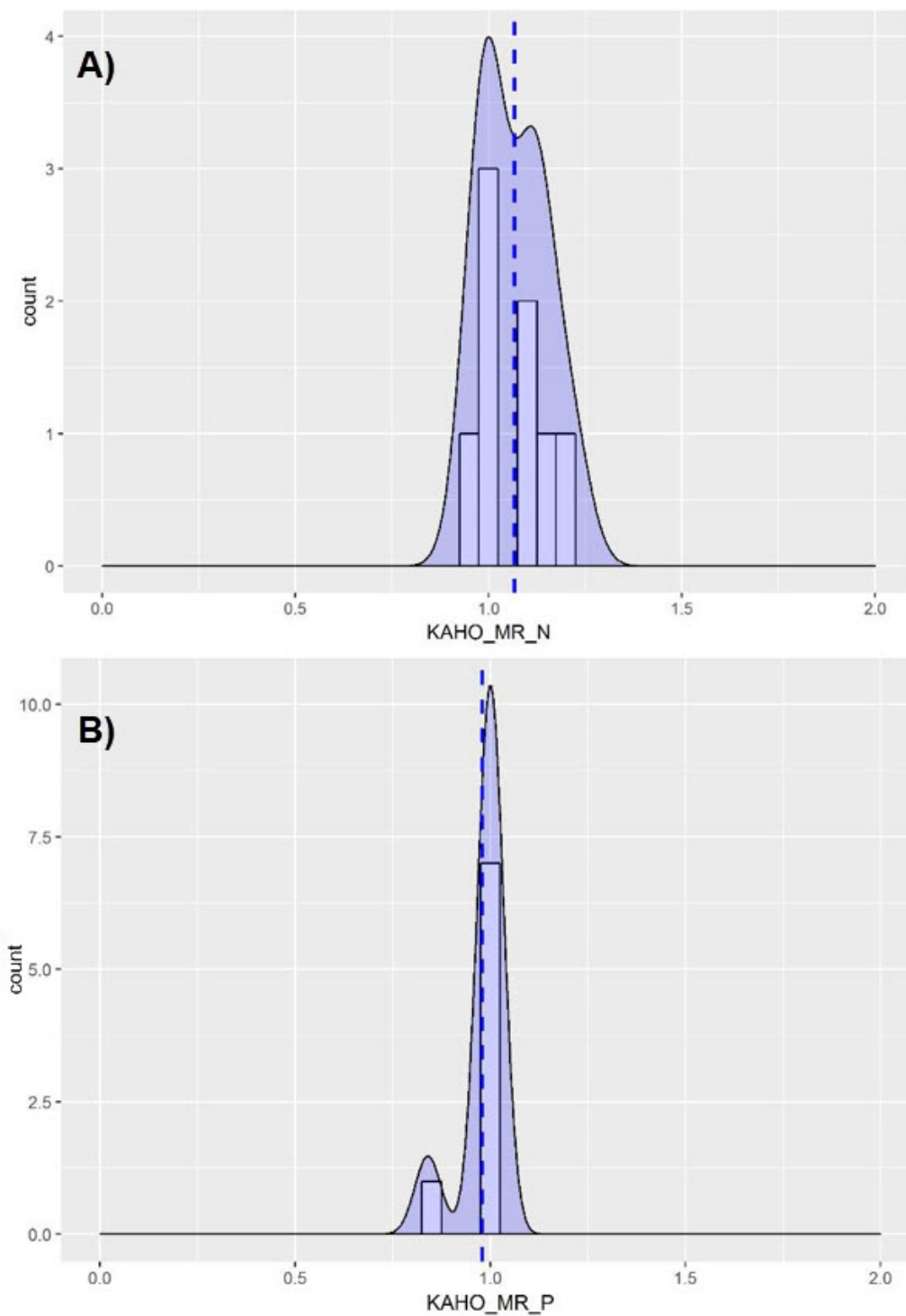


Figure F1. Distribution of dissolved nitrogen (A) and phosphorus (B) fractions in marine waters of Kaloko-Honokōhau National Historical Park.

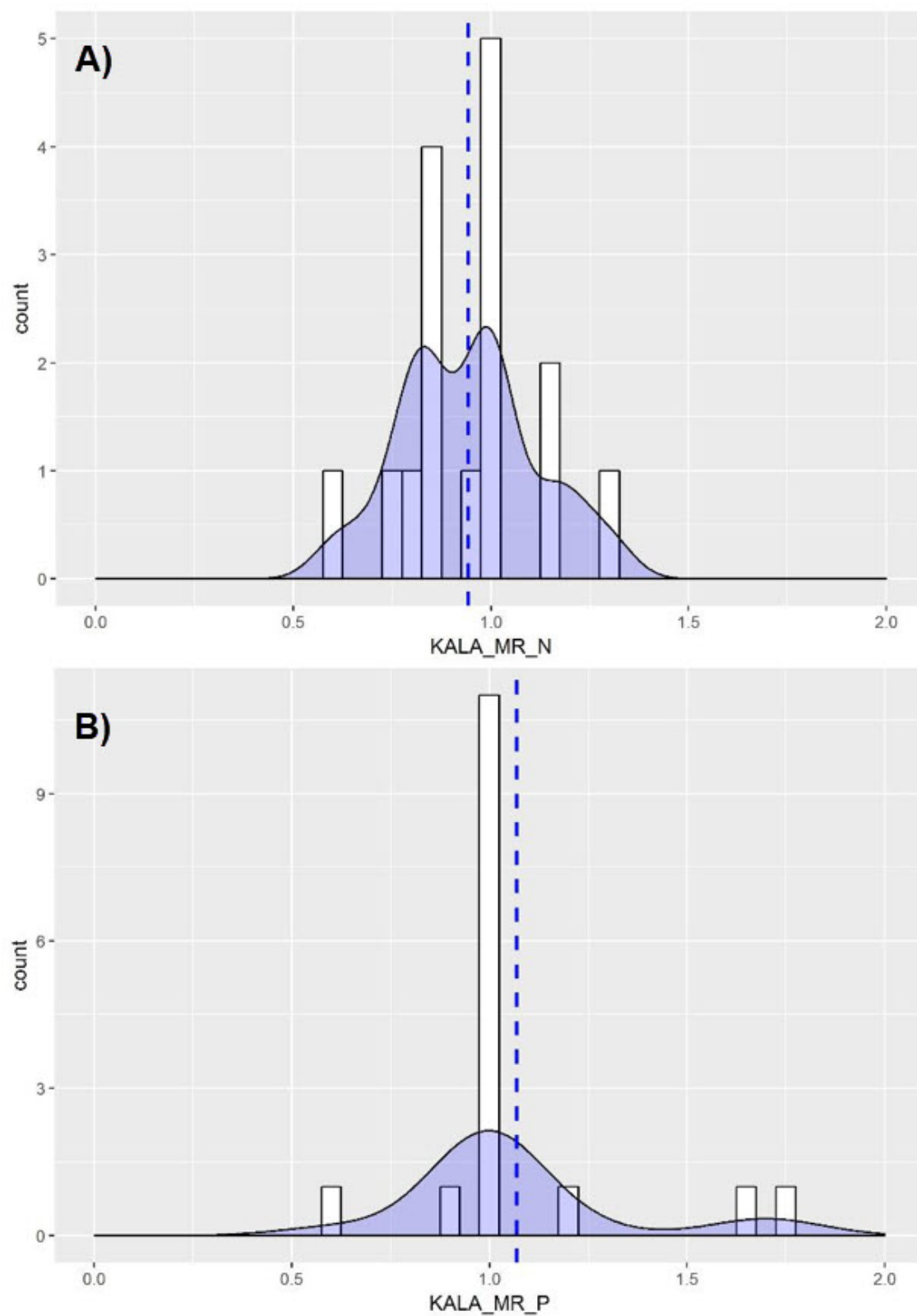


Figure F2. Distribution of dissolved nitrogen (A) and phosphorus (B) fractions in marine waters of Kalaupapa National Historical Park.

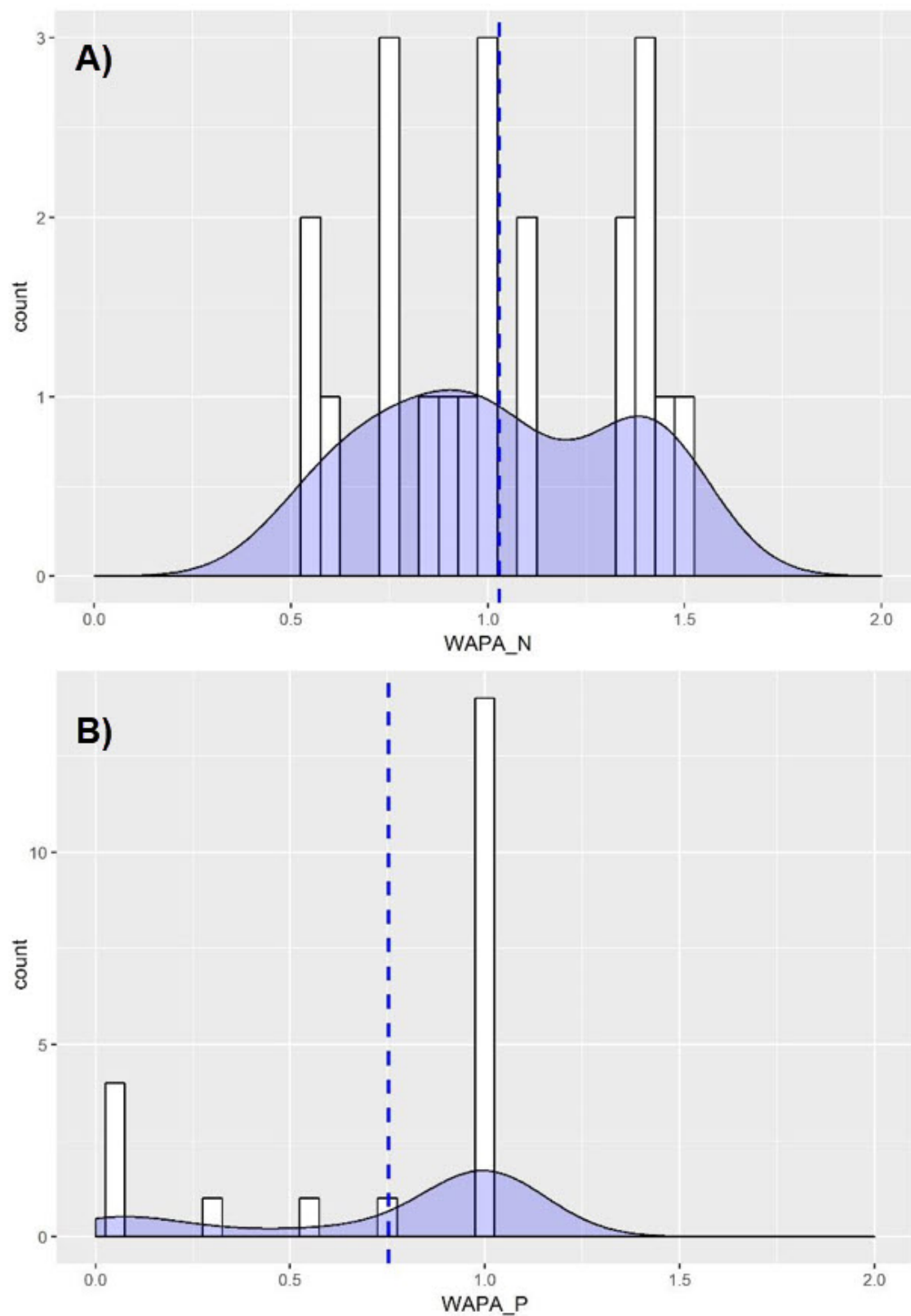


Figure F3. Distribution of dissolved nitrogen (A) and phosphorus (B) fractions in marine waters of War in the Pacific National Historical Park, Asan and Agat units combined.

Appendix G. Comparison of Fixed and Temporary Sites

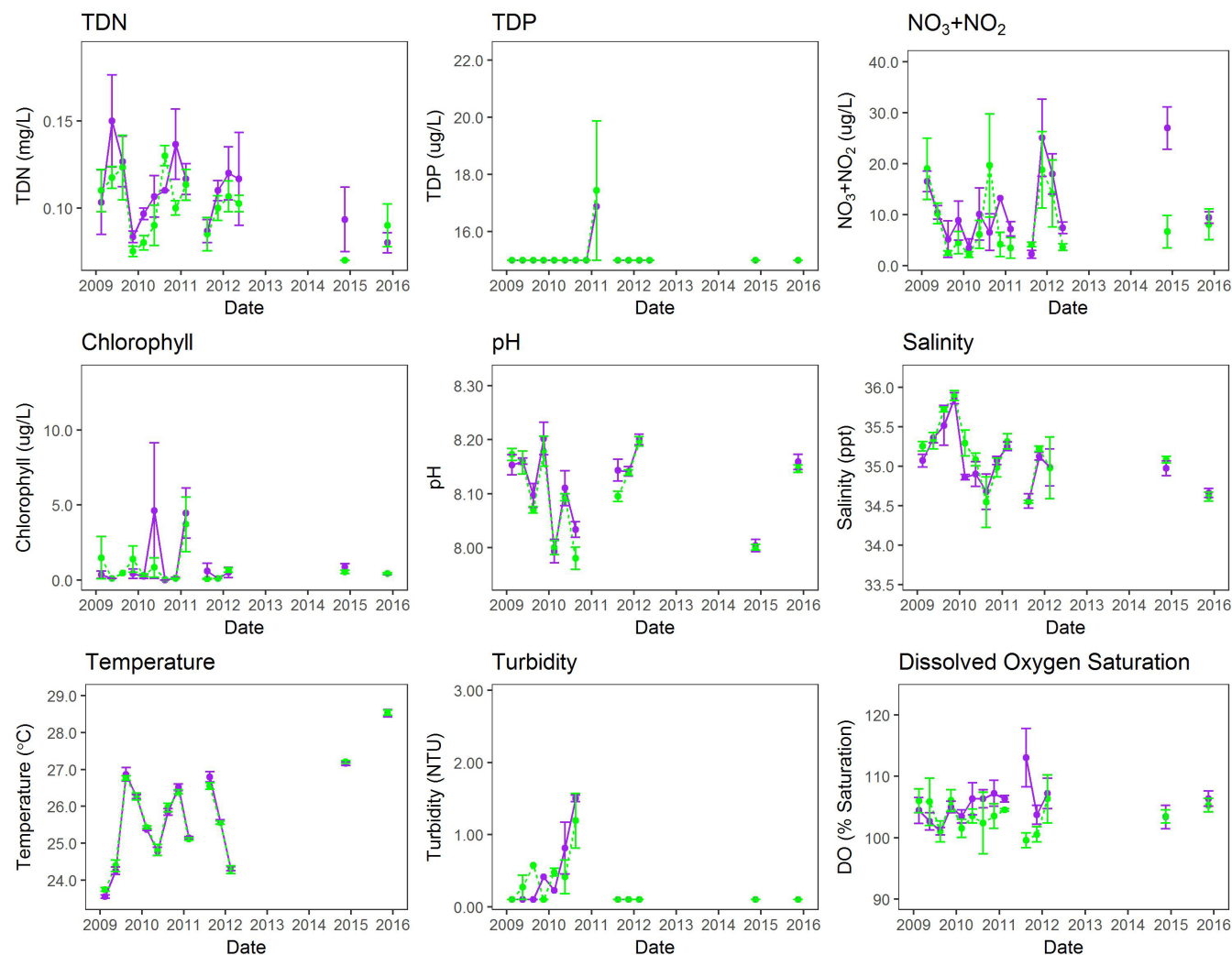


Figure G1. Comparison of surface fixed and temporary sites at Kaloko-Honokōhau National Historical Park, in areas not affected by the Honokohau Small Boat Harbor plume, 2009–2015. Purple = fixed, green = temporary.

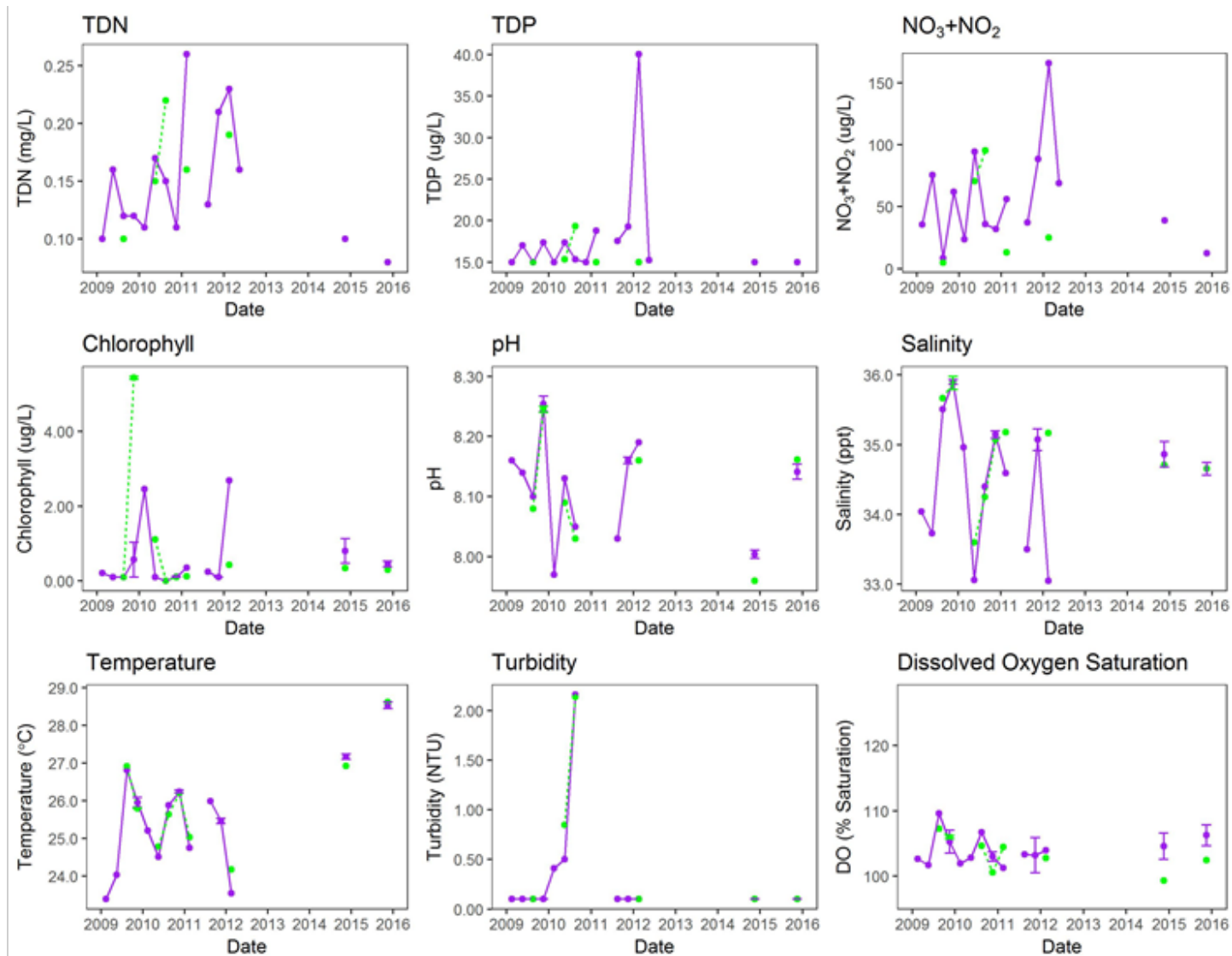


Figure G2. Comparison of surface fixed and temporary sites at Kaloko-Honokōhau National Historical Park, in areas affected by the Honokohau Small Boat Harbor plume, 2009–2015. Purple = fixed, green = temporary.

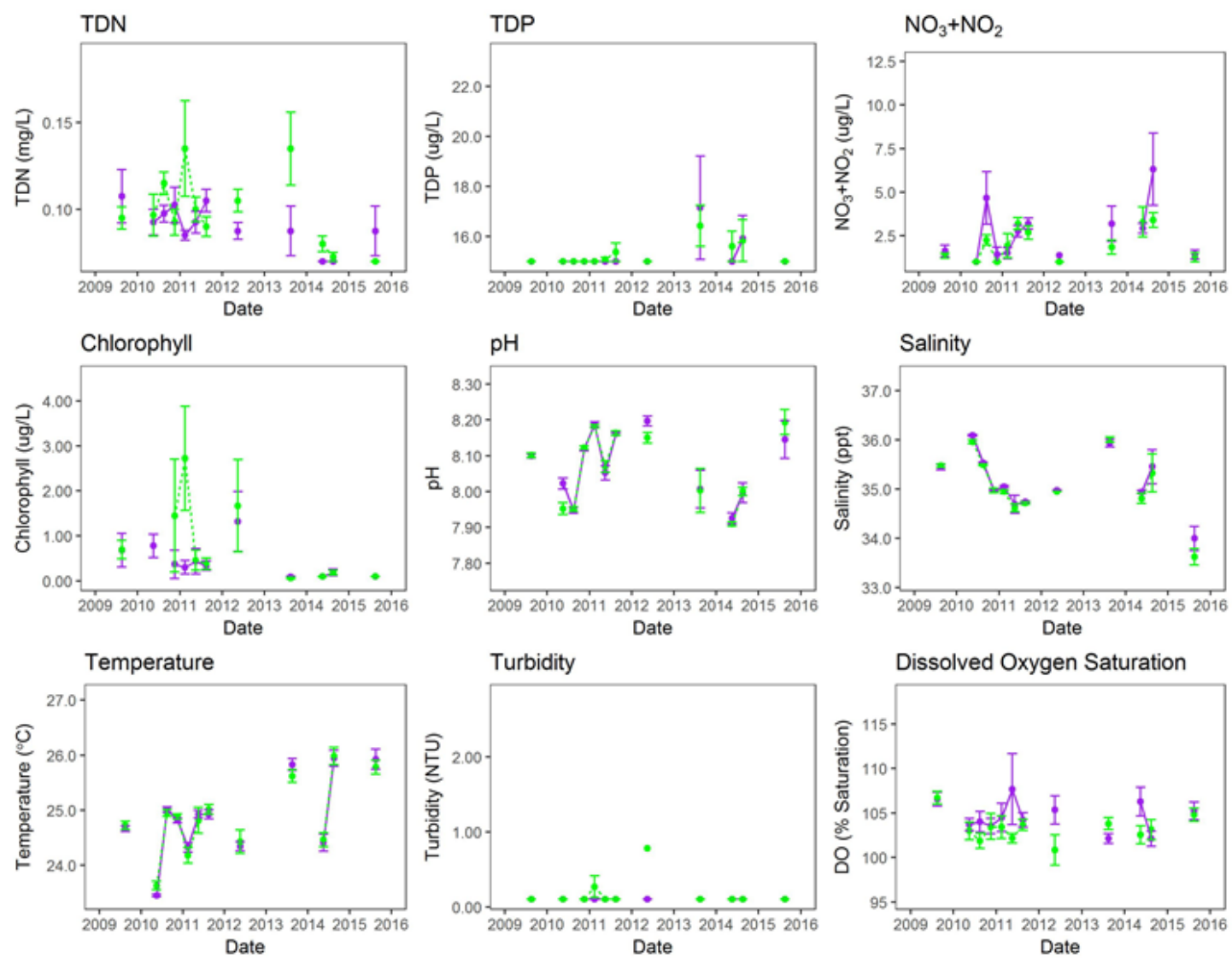


Figure G3. Comparison of surface fixed and temporary sites at Kalaupapa National Historical Park, 2009–2015. Purple = fixed, green = temporary.

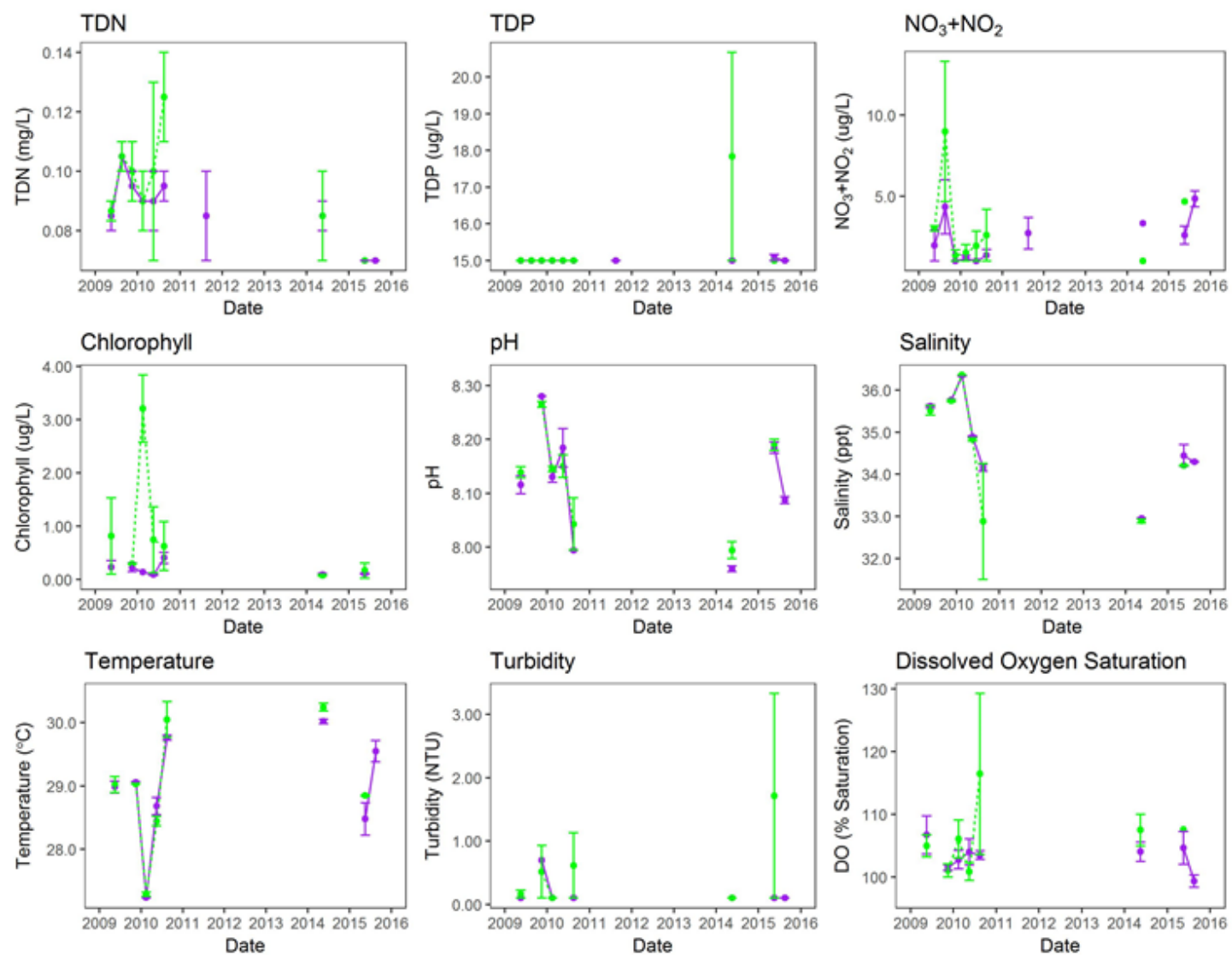


Figure G4. Comparison of surface fixed and temporary sites at War in the Pacific National Historical Park, Asan unit, 2009–2015. Purple = fixed, green = temporary.

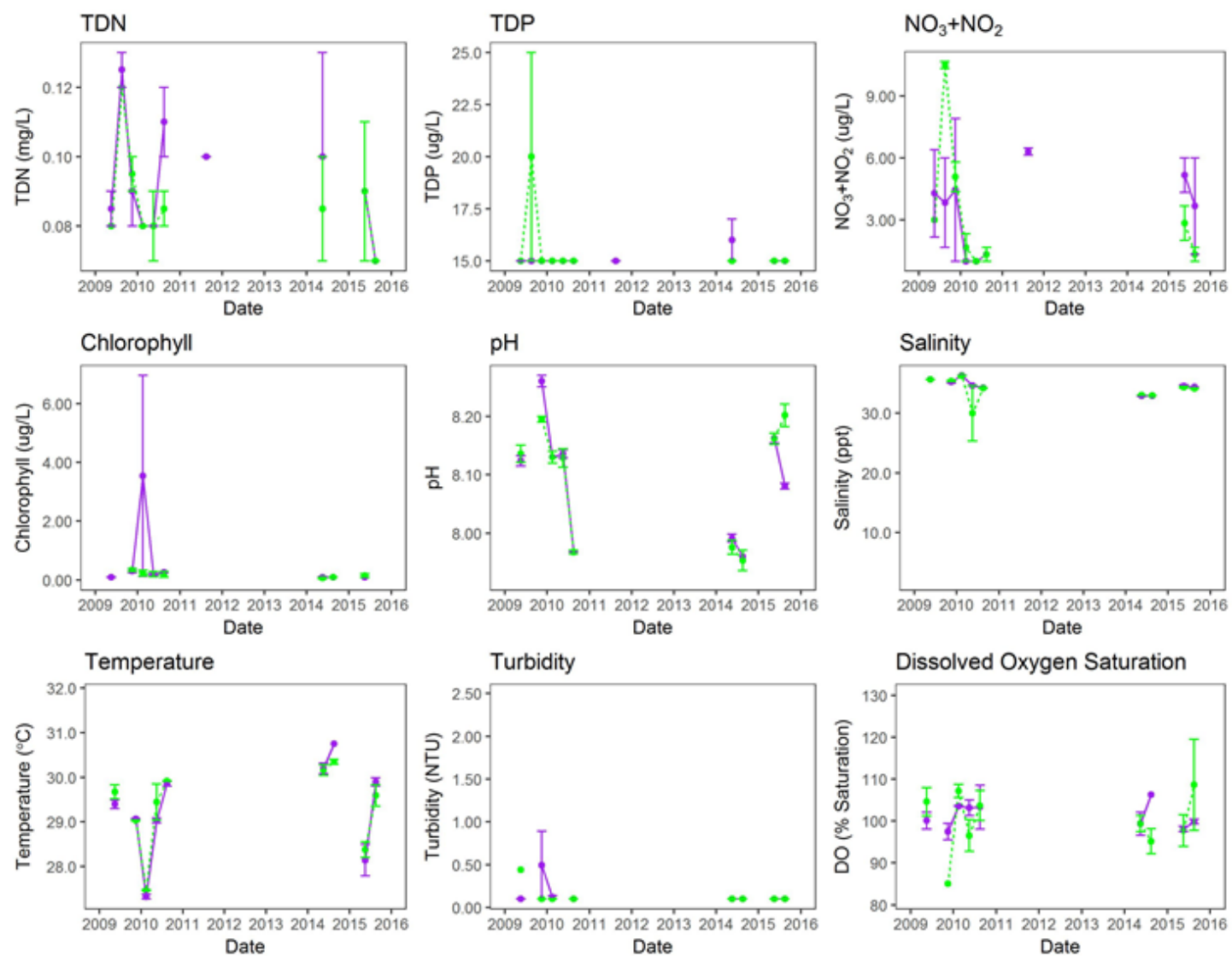


Figure G5. Comparison of surface fixed and temporary sites at War in the Pacific National Historical Park, Agat unit, 2009–2015. Purple = fixed, green = temporary.

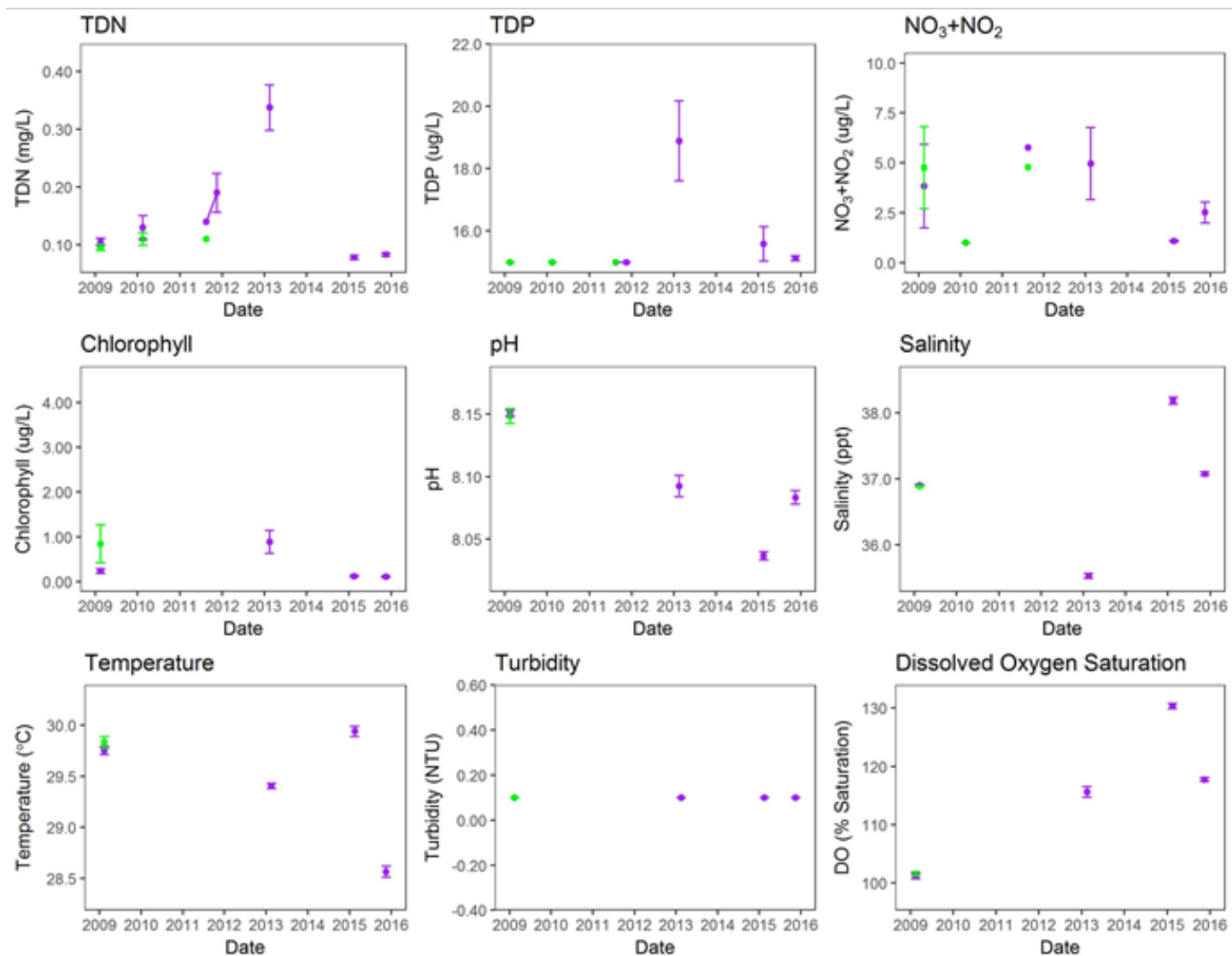


Figure G6. Comparison of surface fixed and temporary sites at National Park of American Samoa, Tutuila, 2009–2015. Purple = fixed, green = temporary.

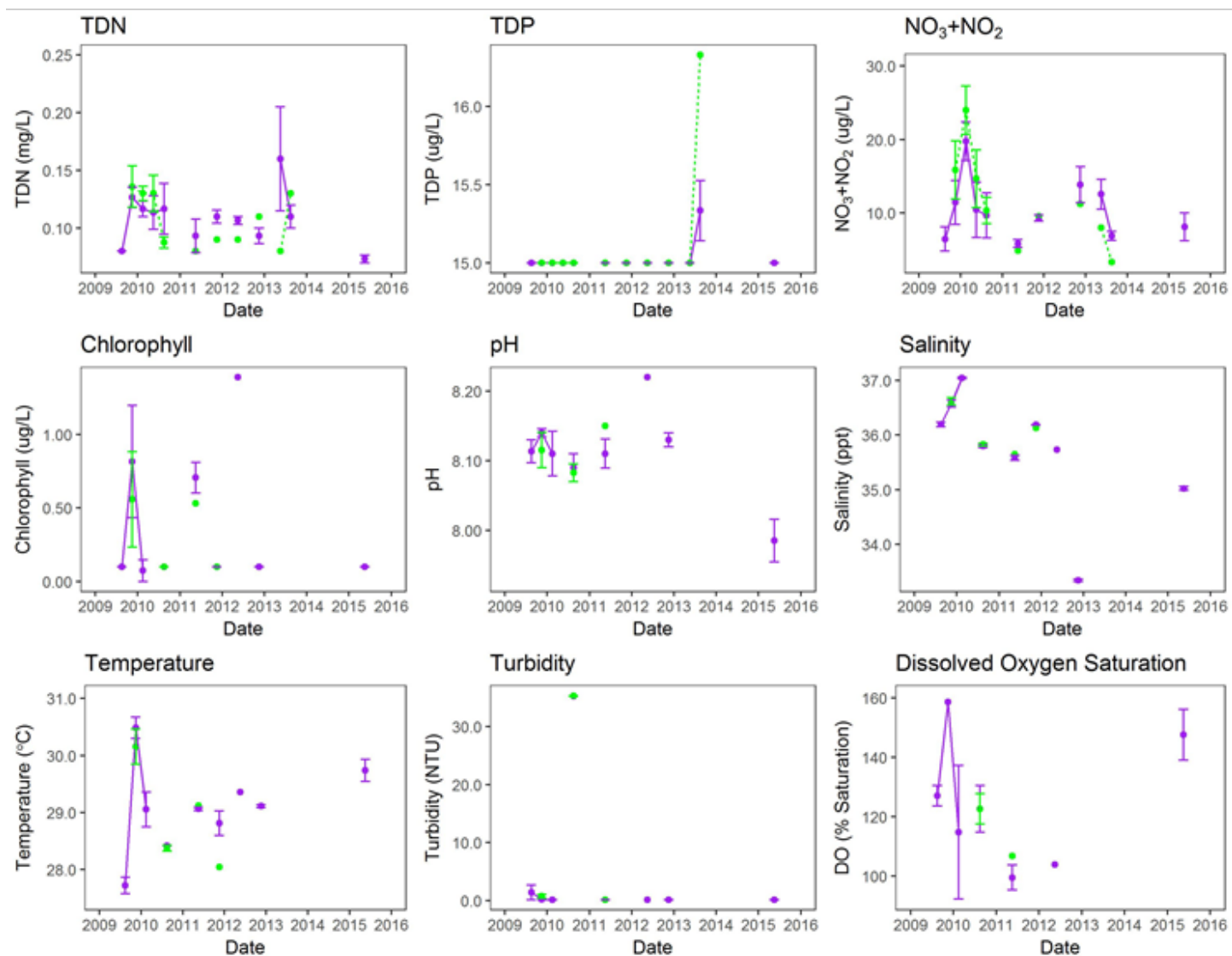


Figure G7. Comparison of surface fixed and temporary sites at National Park of American Samoa, Ofu, 2009–2015. Purple = fixed, green = temporary.

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

NPS 963/175008, January 2021

National Park Service
U.S. Department of the Interior



[Natural Resource Stewardship and Science](#)

1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525