



# **Trends in Water Quality of Waikolu Stream, Kalaupapa National Historical Park, Moloka‘i, Hawaii, 2007–2017**

Natural Resource Report NPS/PACN/NRR—2024/2638



**ON THE COVER**

North Coast of Moloka'i, looking West from the landing at Wailua. Kalaupapa is visible at far right (Lindgren, 1903)

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# **Trends in Water Quality of Waikolu Stream, Kalaupapa National Historical Park, Moloka‘i, Hawaii, 2007–2017**

Natural Resource Report NPS/PACN/NRR—2024/2638

David F. Raikow, Mark Wasser, Amanda L. McCutcheon, Anne Farahi

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

April 2024

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

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Please cite this publication as:

Raikow, D. F., M. Wasser, A. L. McCutcheon, and A. Farahi. 2024. Trends in water quality of Waikolu Stream, Kalaupapa National Historical Park, Moloka'i, Hawaii, 2007–2017. Natural Resource Report NPS/PACN/NRR—2024/2638. National Park Service, Fort Collins, Colorado. <https://doi.org/10.36967/2302153>

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## Executive Summary

Water quality was monitored in Waikolu Stream, Kalaupapa National Historical Park, Moloka‘i, Hawaii from 2007–2017. Water was collected for nutrient analyses and a sonde equipped with multiple probes was used to measure water quality parameters. The sampling regime was based on a split-panel of permanently established or “fixed” sites sampled during each sampling effort, and “temporary” sites of randomly assigned locations, for each sampling effort.

Results included:

- $\text{NO}_3^- + \text{NO}_2^-$  regularly exceeded state water quality criteria.
- TP exceeded state water quality criteria once out of three quarters evaluated.
- Other nutrient concentrations were consistent with Hawaiian streams.
- Waters were clear and well oxygenated.
- Conditions were consistent with similar pacific island streams.
- Dissolved nutrient fractions dominated base flow conditions.
- Seasonality was detected for TDN,  $\text{NO}_3^- + \text{NO}_2^-$ , chlorophyll, pH, oxygen, and temperature.
- Several trends were detected; however, the magnitude of change was small and did not warrant concern.
- Temporal patterns did not obviously correspond to climate conditions.
- Parameters varied spatially to a limited extent, with nitrogen decreasing and temperature, specific conductance, and oxygen increasing from headwaters to the mouth.
- Temporary site conditions were highly correlated with fixed sites and did not provide additional insights.

Water quality in Waikolu Stream was generally good with the exception of  $\text{NO}_3^- + \text{NO}_2^-$  which exceeded state standards. However, concentrations of  $\text{NO}_3^- + \text{NO}_2^-$  were generally consistent with many streams in Hawaii and natural causes of observed concentrations may have included older soils, steep slopes, and high precipitation. Exotic species including ungulates, which are known to occur in Waikolu Valley, could have contributed to elevated N through droppings and soil erosion in the riparian zone. Waikolu Stream TDN, TDP, chlorophyll, pH, turbidity, SpC, and oxygen were consistent with streams in other well-protected NPS watersheds on pacific islands on Maui, Guam, and American Samoa.

Due to the watershed’s small size, the stream’s short length, and because variation or unique conditions were not captured by using split-panel, we recommend reducing the sampling effort. For example, our observations indicate that one easily accessible site in the lower reaches of the stream (FKALA03) displays water quality that reflects the entire stream. We also recommend adding nutrient analytes to better characterize biogeochemical cycling in this stream, including TP, TN,  $\text{NH}_4^+$ , and  $\text{PO}_4$ . A power analysis is underway to evaluate reduction of sample sites. Such a reduction will result in large cost savings for the PACN water quality monitoring program.

## **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, Kelly Moore, Justin Mills, Visa Vaivai, Sylvester Lee, Glauco Puig-Santana, Rebecca Weissinger, Greg Kudray, Ryan Monello, Tara Holitzki, Erik Johnson, and Eric Dinger.

## List of Acronyms

|                                |                                                 |
|--------------------------------|-------------------------------------------------|
| C:                             | Carbon                                          |
| CO <sub>2</sub> :              | 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                |
| KALA:                          | Kalaupapa National Historical Park              |
| N:                             | Nitrogen                                        |
| NH <sup>+</sup> <sub>4</sub> : | Ammonium                                        |
| NHP:                           | National Historical Park                        |
| NO <sup>-</sup> <sub>2</sub> : | Nitrite                                         |
| NO <sup>-</sup> <sub>3</sub> : | Nitrate                                         |
| NOAA:                          | National Oceanic and Atmospheric Administration |
| NPS:                           | National Park Service                           |
| NRDS:                          | Natural Resource Data Series                    |
| NRR:                           | Natural Resource Report                         |
| NTU:                           | Nephelometric Turbidity Units                   |
| ODO:                           | Optical Dissolved Oxygen                        |
| ONI:                           | Oceanic Niño Index                              |
| 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                |
| SpC:                           | Specific Conductivity                           |
| SRP:                           | Soluble Reactive Phosphorus (Phosphate)         |
| STORET:                        | Storage and Retrieval (water quality database)  |
| 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                 |
| WRD:                           | Water Resources Division                        |

# Introduction

Water quality is widely used as an indicator of freshwater-ecosystem condition. 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, and recreational use, water quality was adopted as a vital sign monitored by the NPS Inventory and Monitoring Division (IMD), Pacific Island Network (PACN, Figure 1). The primary goals of PACN are to determine the status and trends of indicators of the condition of park ecosystems, provide early warnings of abnormal conditions in ecosystems to park management, and provide data to better understand the dynamics of park ecosystems (HaySmith et al. 2005). The primary objectives of the PACN water quality program include determining the range, spatial patterns, and temporal trends of water quality parameters in selected streams of Pacific Island National Parks (Jones et al. 2011). Secondary objectives included determining particulate and dissolved nutrient fractions and the general evaluation of methods including potential of redundancy of sample sites. Water quality sampling is also co-located with the PACN stream animal monitoring protocol (Brasher et al. 2011). Natural Resource Reports (NRRs) published by IMD present 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. This report specifically addresses Waikolu Stream in Kalaupapa National Historical Park (NHP), Island of Moloka‘i, Hawaii. Information on the water quality of Waikolu Stream has previously been reported in Raikow and Farahi (2014a). Park managers can use this information to evaluate resource conditions, potential impacts, and mitigation measures for parks and watersheds.

## General Biogeochemistry

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 1). Characteristics of nutrient species important to water quality include being dissolved or particulate, being organic (contained within or derived from organisms) or inorganic, and being labile (easily used by organisms) or recalcitrant (less easily 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.

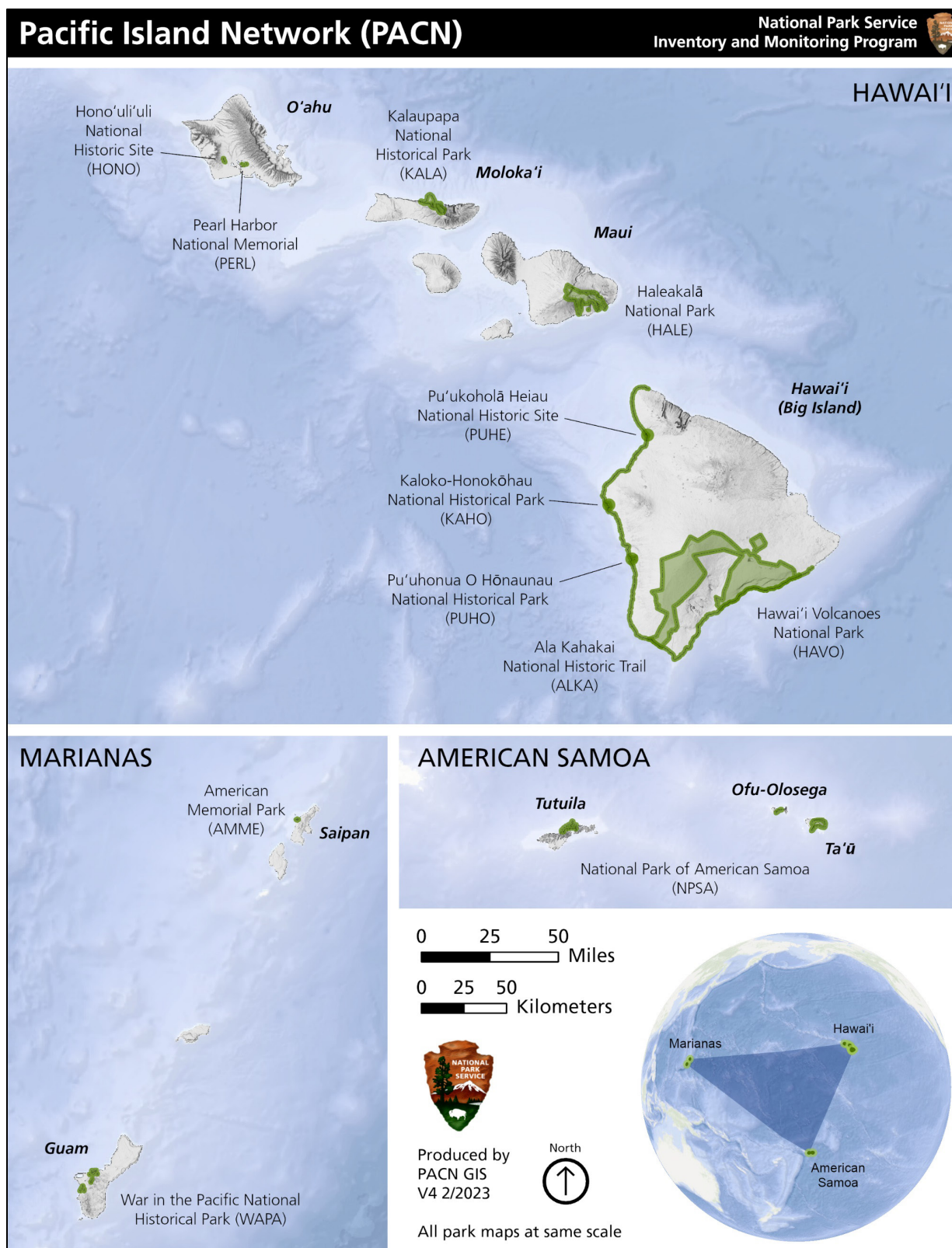


**Figure 1.** Park units of the Pacific Island Network, Inventory and Monitoring Division, National Park Service.

**Table 1.** Phosphorus (P) and Nitrogen (N) nutrient species found in aquatic ecosystems.

| Nutrient Species             | Symbol                       | Components                                                                                                                                        |
|------------------------------|------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------|
| Total Phosphorus             | TP                           | Particulate Phosphorus + Total Dissolved Phosphorus                                                                                               |
| Particulate Phosphorus       | PP                           | Algae, zooplankton, detritus, P in or on inorganic particles                                                                                      |
| Total Dissolved Phosphorus   | TDP                          | Soluble Reactive Phosphorus + Dissolved Organic Phosphorus                                                                                        |
| Soluble Reactive Phosphorus  | SRP                          | PO <sub>4</sub> , phosphate, orthophosphate, or inorganic phosphorus                                                                              |
| Dissolved Organic Phosphorus | DOP                          | P in organic molecules derived from organisms                                                                                                     |
| Total Nitrogen               | TN                           | Particulate Nitrogen + Total Dissolved Nitrogen                                                                                                   |
| Particulate Nitrogen         | PN                           | Algae, zooplankton, detritus, N in or on inorganic particles                                                                                      |
| Total Dissolved Nitrogen     | TDN                          | Dissolved Inorganic Nitrogen + Dissolved Organic Nitrogen                                                                                         |
| Dissolved Inorganic Nitrogen | DIN                          | NH <sub>4</sub> <sup>+</sup> + NO <sub>3</sub> <sup>-</sup> + NO <sub>2</sub> <sup>-</sup>                                                        |
| Dissolved Organic Nitrogen   | DON                          | N in organic molecules derived from organisms                                                                                                     |
| Ammonium                     | NH <sub>4</sub> <sup>+</sup> | In solution ammonium exists in equilibrium with ammonia and can be reported as “total ammonia” (NH <sub>4</sub> <sup>+</sup> + NH <sub>3</sub> ). |
| Nitrate                      | NO <sub>3</sub> <sup>-</sup> | Often reported as NO <sub>3</sub> <sup>-</sup> + NO <sub>2</sub> <sup>-</sup>                                                                     |
| Nitrite                      | NO <sub>2</sub> <sup>-</sup> | Often reported as NO <sub>3</sub> <sup>-</sup> + NO <sub>2</sub> <sup>-</sup>                                                                     |

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 N<sub>2</sub>-fixing crops, spreading N<sub>2</sub>-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).

### Biogeochemistry of Pacific island streams

Hawaiian streams cannot be directly compared to continental tropical or sub-tropical streams with respect to nutrients due to the small sizes, volcanic origin, geologic youth, and great disparity in rainfall between windward and leeward sides of the Hawaiian Islands. For example, TDP concentrations in major South American river systems including the Amazon range from ~10 ug/L or less in headwaters to 50–60 mg/L downstream (Dudgeon 2008). In contrast, Raikow and Farahi (2014a) reported a median annual TDP concentrations in Waikolu Stream, which is comparable in size to small channels of Amazonian headwaters, of ~40 mg/L from 2007 to 2011. 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).

Discharge in small tropical rainforest streams typically shows high variation reflecting spates produced by short intense rainfall events (Dudgeon 2008). Streams on the north shore of Moloka'i, while being sub-tropical, also display this pattern (Figure 2). It is important to note that sampling for water quality under this program specifically targets baseflow conditions.

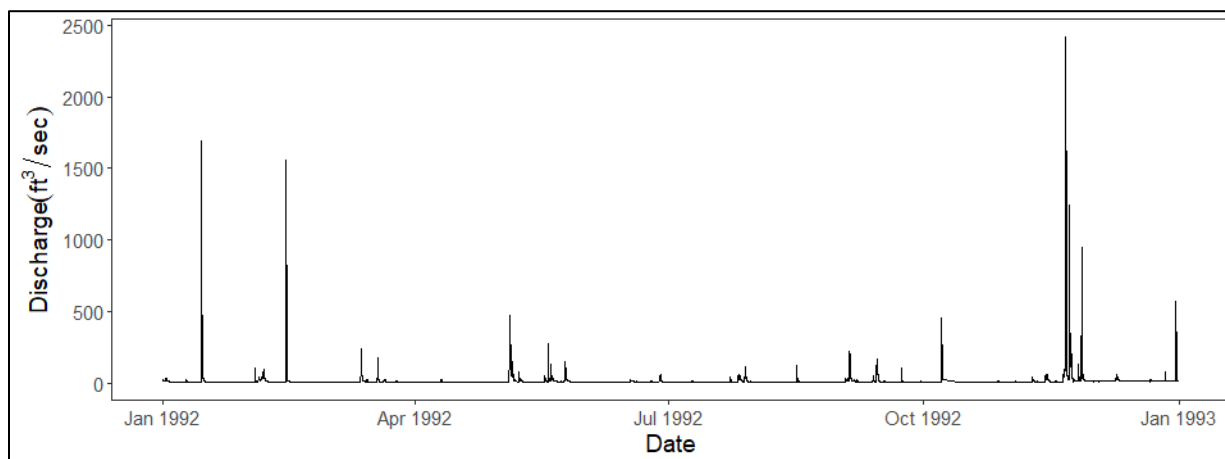


**Figure 2.** 1992 discharge (Q) in Waikolu Stream, Kalaupapa National Historical Park, Moloka'i, HI, USGS monitoring location 16408000.

Drainage network patterns are relevant to the choice of water quality sample site dispersion, in order to balance accurate characterization of the watershed and effort (e.g., number and location of sample sites). The drainage networks of Hawaiian streams are frequently confined to highly eroded valleys producing parallel (elongated branching channels running parallel to each other), or trellis (unbranched tributaries entering the main channel at right angles) spatial patterns, rather than the more common dendritic (broadly branching tributaries) patterns often found in continental drainage networks. Waikolu stream displays a drainage network that is a combination of parallel and trellis (Figure 3). Here, due to steep slopes, the intermittent nature of tributaries, the relatively short length of first and second order tributaries, and logistical challenges of accessing headwaters, only the main channel was sampled.

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. 2016). Leeward sides of islands receive less precipitation, and the establishment of surface drainage channels (streams) can be thwarted when precipitation penetrates the surface (Oki 1999, Moore 1999). Rain becomes fresh groundwater and mixes with seawater infiltrating terrestrial aquifers and creating brackish groundwater lenses (Moore 1999). Underlying geological features such as lava tubes can transmit water quickly, while lava dikes can impede groundwater flow, resulting in perched aquifers (Oki 1999, Taboroši et al. 2004, Knee and Paytan 2011).

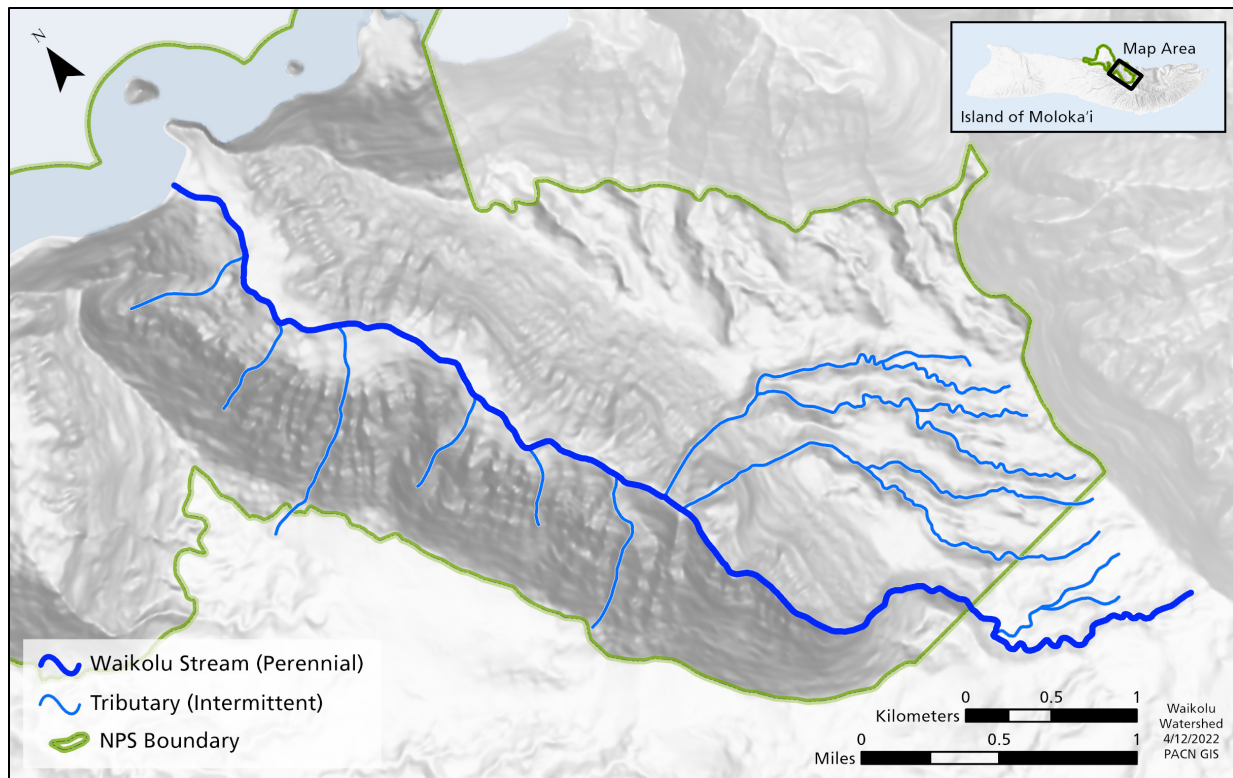


**Figure 3.** Drainage network of Waikolu Stream.

### State Water Quality Standards

Water quality criteria for streams are defined in §11-54-5.1b of the State of Hawaii Department of Health Water Quality Standards (State of Hawaii 2012, Table 2). Streams in the national parks of Hawaii are classified as Class 1.a protected waters (State of Hawaii 2012). As such the “wilderness character” of these waters is to be protected, and waste discharge into these waters is generally prohibited. Criteria measured in the water column are defined for the wet season (November 1–April 30) and the dry season (May 1–October 31). Criteria are defined for TP, TN, nitrate + nitrite ( $\text{NO}_3^- + \text{NO}_2^-$ ), total suspended solids, and turbidity in terms of a geometric mean not to be exceeded, and values not to be exceeded 10% and 2% of the time. The arithmetic mean, or average, of a set of values is defined as the sum of those values divided by the count, and the geometric mean is the  $n$ th root of the product of  $n$  values. Note that measurements of TDP and TDN are not directly comparable to the TP and TN state criteria. That is, measured dissolved concentrations that exceed standards for total concentration indicate standards have been exceeded. However, while measured dissolved concentrations lower than standards for total concentrations do not indicate that standards have been exceeded, exceedance of total concentrations could still exist.

**Table 2.** State of Hawaii specific inland water criteria for streams (State of Hawaii 2012).

| Parameter              | Unit                               | Season           | Geometric mean<br>not to exceed<br>the given value | Not to exceed<br>the given value<br>more than 10%<br>of the time | Not to exceed<br>the given value<br>more than 2%<br>of the time |
|------------------------|------------------------------------|------------------|----------------------------------------------------|------------------------------------------------------------------|-----------------------------------------------------------------|
| Total Phosphorus       | $\mu\text{gP} \cdot \text{L}^{-1}$ | Wet <sup>1</sup> | 50.0                                               | 100.0                                                            | 150.0                                                           |
|                        | $\mu\text{gP} \cdot \text{L}^{-1}$ | Dry <sup>2</sup> | 30.0                                               | 60.0                                                             | 80.0                                                            |
| Total Nitrogen         | $\text{mgN} \cdot \text{L}^{-1}$   | Wet              | 0.250                                              | 0.520                                                            | 0.800                                                           |
|                        | $\text{mgN} \cdot \text{L}^{-1}$   | Dry              | 0.180                                              | 0.380                                                            | 0.600                                                           |
| Nitrate + Nitrite      | $\mu\text{gN} \cdot \text{L}^{-1}$ | Wet              | 70.0                                               | 180.0                                                            | 300.0                                                           |
|                        | $\mu\text{gN} \cdot \text{L}^{-1}$ | Dry              | 30.0                                               | 90.0                                                             | 170.0                                                           |
| Total Suspended Solids | $\text{mg} \cdot \text{L}^{-1}$    | Wet              | 20.0                                               | 50.0                                                             | 80.0                                                            |
|                        | $\text{mg} \cdot \text{L}^{-1}$    | Dry              | 10.0                                               | 30.0                                                             | 55.0                                                            |
| Turbidity              | NTU                                | Wet              | 5.0                                                | 15.0                                                             | 25.0                                                            |
|                        | NTU                                | Dry              | 2.0                                                | 5.5                                                              | 10.0                                                            |

<sup>1</sup> Wet season: November 1–April 30.

<sup>2</sup> Dry season: May 1–October 31.

### Moloka‘i Irrigation System

Located on the wet windward side of the island, Waikolu Stream is a source of water for agriculture and residential use on the dry leeward west side of the island, through the Moloka‘i Irrigation System, completed in 1962 (Figure 4). The system consists of four surface water diversion dams and six wells in Waikolu Valley, a pumphouse, a 5.1-mile-long tunnel through which diverted water flows, a flume, pipes, and reservoir. Water is diverted by both gravity from diversion dams, active pumping from individual wells and pumping from a dam downstream of the tunnel entrance (Pump House, Figure 4). During the study period the system diverted over  $10^9$  gallons of water annually. Diversion is known to cause some sections of the stream channel to dry in summer and fall months (“sections III and IV” in Water Resource Associates 1999). These sections are high in the valley upstream of the pumphouse and sites regularly sampled by PACN for water quality and stream animals. Management of the system, including the Waikolu Hydrologic Unit 4003 encompassing Waikolu Stream, was altered in 2022 by the revision of the Instream Flow Standards (IFS), which will increase flow through Waikolu Stream (State of Hawaii 2022). The alteration will affect a section of stream that experiences drying when water is otherwise diverted. Sites sampled by PACN for both water quality and stream animals (e.g., FKALA08) may be affected significantly by this change while downstream sites may not experience a measurable change.

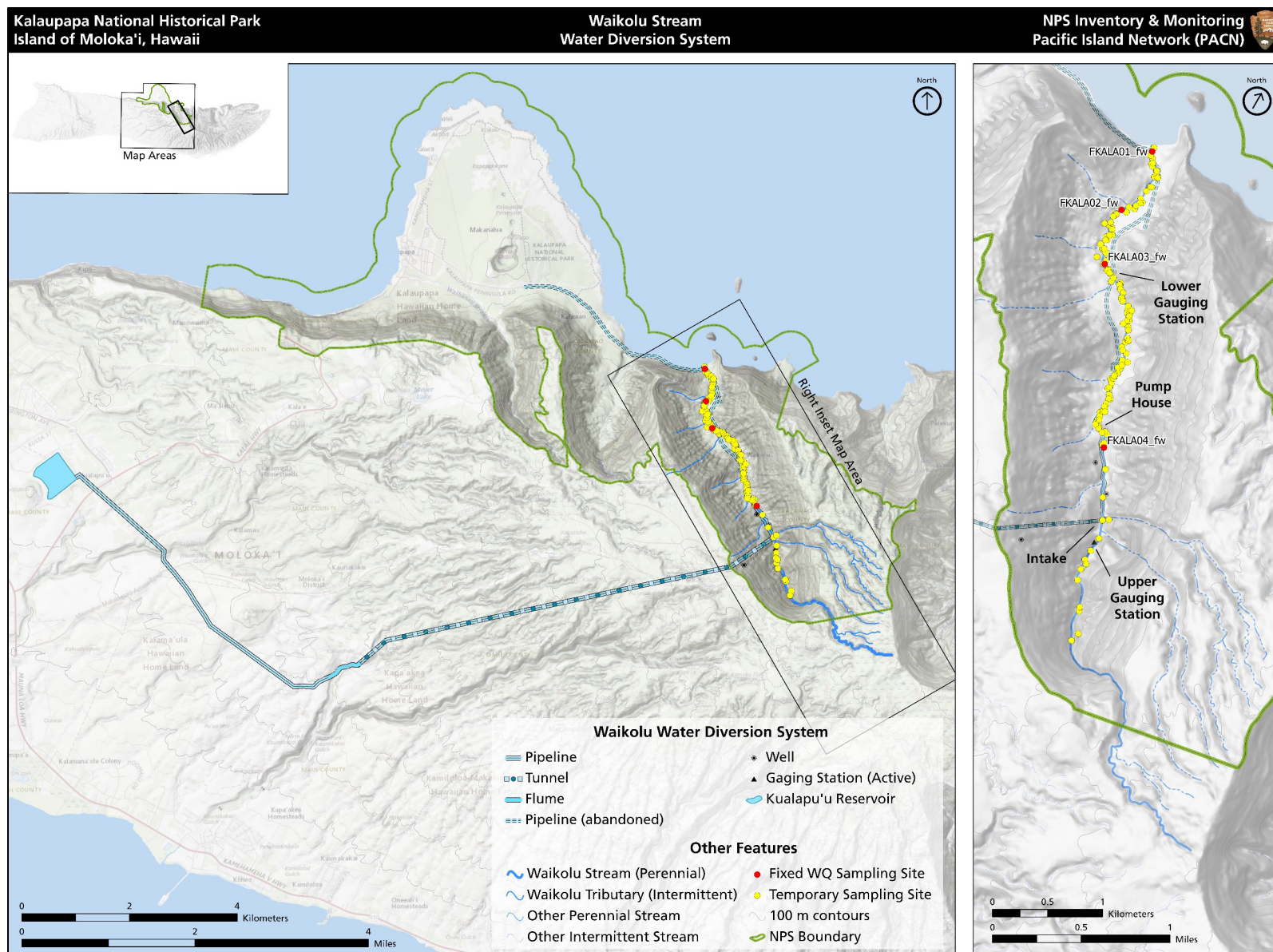


Figure 4. Waikolu water diversion system.

## Global-Scale Climate Phenomena

The El Niño Southern Oscillation cycle (ENSO, reviewed by Wang et al. 2016) has the potential to affect streams on Pacific islands. During neutral conditions, westerly trade winds push warm surface water to the western Pacific, with subsequent cool water upwelling in the east. The resulting 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 Pacific water to extend across the Pacific, thereby intensifying the temperature differential and resulting in more 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 causing more rain in the Eastern and Central Pacific with drier conditions in the west. Generalized effects on Pacific islands depend on their location in the Pacific (Sutton et al. 2016). ENSO effects occur in the Western Pacific first and move eastward over time (Rupic et al. 2018). In Hawaii, above average rainfall generally occurs during El Niño phases followed by drier than average conditions (Rupic et al. 2018). Factors such as ENSO have the potential to 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 the primary channel of Waikolu Stream (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:

- **Location within the watershed.** Conditions could vary as a function of position within the watershed, specifically 1) headwaters compared to downstream sites including those near the mouth that could be influenced by the ocean, diversions, or tributaries and 2) point sources of inputs from riparian areas could cause localized and/or downstream impacts.
- **Flood stage.** The estimation of “ordinary” or baseline parameter value ranges and long-term trends must exclude storms, surface runoff discharge events, or other short-term disturbances. Though natural, such occurrences are short-term deviations from baseflow conditions, and thus confound evaluation of long-term trends in studies not specifically designed to capture such events. 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

Kalaupapa NHP 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 with ~2 million year old strata are derived from an erosional volcanic stage (Zielger 2002). The northern Moloka'i coastline receives very high annual rainfall (2–3m per year, Giambelluca et al. 2013). Deep valleys drained by streams discharge freshwater to nearshore environments. Waikolu Stream drains a watershed of 12.2 km<sup>2</sup> in Waikolu Valley and has been classified as 100% conservation, although only 89% of the Waikolu stream watershed lies within the national park (HDAR 2008).

Data were collected quarterly from 2007–2017 using methods described in version 1.0 of the PACN water quality protocol (Jones et al. 2011; described below). Water was collected for nutrient analyses, a sonde equipped with multiple probes was used to measure water quality parameters, pictures were taken, and global positioning system coordinates, site notes, and weather conditions recorded.

### Sampling Regime

The sampling regime was based on a split-panel of four permanently established or “fixed” sites sampled during each sampling effort, and four randomly located “temporary” sites designated for each sampling effort. Site names used by PACN were formatted to designate fixed or temporary sites (“F” or “T” respectively), park (KALA), an identity number (e.g., 01), and habitat type (“fw” for freshwater); e.g., “FKALA01\_fw” (Figure 5). Names for temporary sites were based on the date of sampling. e.g., “FKALA01\_20081014\_fw”. Sites were sampled during quarterly trips from November 2007 to December 2017. A new set of four temporary sites were chosen at random for quarterly trips. Additional fixed and temporary sites were sampled in the headwaters above FKALA04, but these sites were sampled intermittently.

### Water Collection

From 2007 to 2013 water was collected using a new or acid-washed 140 ml syringe just below the stream surface to avoid disturbance of sediment on the bottom or collection of floating material. This water was then discarded away from the collection location to rinse the syringe. Water was again collected using the rinsed syringe. An in-line filter holder and 0.47 µm GF/F filter were then placed on the syringe. From 2014 to 2017 water was filtered through an acid-washed filter tower and 0.47 µm GF/F filter. Filtered water was used to rinse each sample bottle three times, discarding water between each rinse. For all samples (2007–2017), three independent-grab 140 ml replicate samples were taken at each site. Sample bottles were placed on ice in the field inside an insulated backpack. Samples were transported to the headquarters of Kalaupapa NHP either on the day of collection and then frozen or kept on ice in the field before transport to the natural resource management office. Samples were later transported to Hawai'i Volcanoes National Park while frozen. Samples were delivered to the EPSCoR Analytical Laboratory at the University of Hawai'i at Hilo Marine Science Department, 200 W. Kawili St., Hilo, Hawaii 96720 for chemical analysis. Analytes and their minimum detection limits included TDP (15.0 micrograms per liter or µg/L), TDN (0.070 milligrams per liter or mg/L), and NO<sub>3</sub><sup>-</sup> + NO<sub>2</sub><sup>-</sup> (1.0 µg/L).

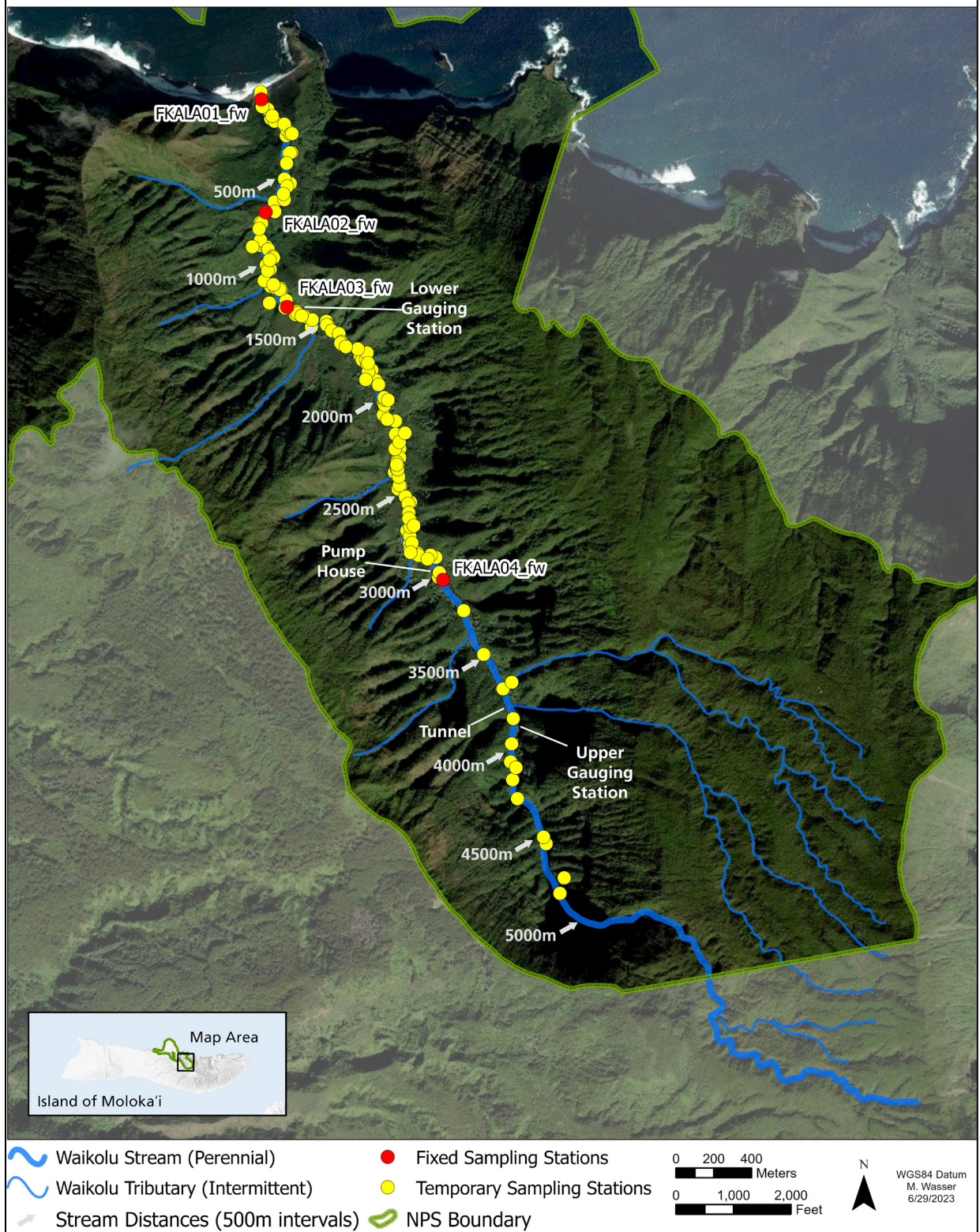


**Figure 5.** Sample sites in Waikolu Stream.

A multi-parameter sonde (YSI 6600 or EXO2) was calibrated within a few days before commencing field sampling. The sonde was used to measure depth (m), temperature (°C), specific conductivity (SpC) in milli-Siemens per centimeter (mS/cm), pH, optical dissolved oxygen concentration (ODO) in mg/L, chlorophyll in µg/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, but salinity is not reported here. Dissolved oxygen in percent saturation (% ODOsat) was calculated from ODO and temperature. At each site, the sonde recorded readings every 30 seconds and allowed to log readings for ten minutes.

### **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 whether total nitrogen and phosphorus or total dissolved nitrogen and phosphorus were to be measured. Both filtered and unfiltered samples were collected from 2014 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%.

### **Climate Data**

Precipitation data was obtained from the Remote Automatic Weather Stations (RAWS) stations: Makapulapai RAWS (NESDIS ID = FA9024CE) located on the Kalaupapa peninsula, and Pu'u Ali'i RAWS Near Kaunakakai 9NE (32D6052E) located in the headwaters of Waikolu Valley. Both stations are operated by NPS and are part of the PACN Climate Protocol (Schlappa et al. 2011). Oceanic Niño Index (ONI) data was obtained from NOAA (2022).

### **Data Management**

All data were entered into PACN databases (e.g., PACN 2019). Data were downloaded from the YSI handheld unit and readings were 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 control of measurements in laboratory nutrient analyses.

### **Spatial Analysis**

Spatial patterns were evaluated along the length of the stream. In order to remove temporal variation, the dataset was normalized based on the median value of each sampling event. The median value for each parameter by sampling event was subtracted from each record and linear regression performed on the normalized dataset.

## Estimation of Parameter Value Ranges

The ranges of water quality parameter values were estimated for Waikolu Stream by summarizing the distribution of data collected during the entire study period. All data for Waikolu 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 (See Results section, Figure 7).

## Trend Analysis

Choice of statistical methods for trend analysis was influenced by the nature of the 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 2018). The non-parametric Mann-Kendall Tau was used to assess trends in nutrients, chlorophyll, and turbidity when 50% or less of the data were censored. The seasonal Mann-Kendall test would be 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). Mann-Kendall tests were evaluated using the EnvStats package for R (Millard 2013). Mixed models were evaluated with the lmer function in the lmerTest package (Kuznetsova et al. 2016).

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 notes on censoring below). Variation in sample values should be most influenced by external factors.

Data censoring occurs when there is a limit to the values a parameter may display or be detected. Here nutrients, chlorophyll, and turbidity have 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). 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 trends.

Seasonality was assessed for parameters prior to performing linear mixed model tests to determine if seasonal factors should be included in the model (Appendix A). 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 May through October (dry season for Hawaii). 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. It is necessary to exclude a time-interval, e.g., “q4” and “dry”, in tests as these serve as references for the model. Two tests for seasonality were performed for each parameter, based on quarterly data and data grouped into wet and dry seasons. Season was included in models only when strong evidence of seasonality was suggested, which was chosen to be having three significant tests. Season was included in the models of only a handful of trend tests.

Linear mixed models allow 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). This model must be adapted to the ecosystem under analysis. For example, whereas sample depth may be relevant to the analysis of marine samples, here distance from the stream mouth was included as a term due to the linear flow of water through a stream. 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 A) included fixed factors for time (WYEAR) 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 Time and Distance from the mouth. 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. The factor “Distance from mouth” tests for a spatial effect, i.e., location along the linear flow path of the stream. 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).

### **Redundant Sampling Analysis**

To evaluate whether monitoring of water quality in Waikolu Stream could be accomplished more efficiently with less sample sites, correlations between sites were evaluated. In general, if fewer sites than currently sampled, or perhaps a single site, reflected patterns observed across the entire stream, then long-term monitoring might be accomplished at greatly reduced cost and effort. In particular, since water flows downstream, it is possible that a downstream site could represent the entire stream, if temporal patterns at that site are correlated with patterns seen as derived from all sites. Each

correlation was conducted for each water quality parameter using the `rcorr` function in the `Hmisc` package in R (Harrell 2023) and Pearson (parametric) or Spearman rank (non-parametric) correlation methods as appropriate according to censoring. Comparisons included:

- Fixed vs. temporary sites
- FKALA01 vs. all sites excluding FKALA01
- FKALA02 vs. all sites excluding FKALA02
- FKALA03 vs. all sites excluding FKALA03
- FKALA04 vs. all sites excluding FKALA04
- FKALA01 vs. Upper reach sites (FKALA08, 09, and 10)
- FKALA02 vs. Upper reach sites (FKALA08, 09, and 10)
- FKALA03 vs. Upper reach sites (FKALA08, 09, and 10)
- FKALA04 vs. Upper reach sites (FKALA08, 09, and 10)
- Upper reach sites (FKALA08, 09, and 10) vs. All sites excluding FKALA08, 09, and 10

In correlation analyses salinity was excluded because it is calculated from specific conductance, as was oxygen saturation because it is calculated from oxygen concentration and temperature. Turbidity was excluded from correlation analysis because values were essentially at the detection limit and did not vary greatly across the stream. Absolute values were used in calculations of mean and median R.

### **Comparison to other streams**

Results were compared to other streams monitored by PACN including those in NPSA (Fagatuitui Stream, Leafu Stream, Lafuti Stream, Amalau Stream, see Raikow and Farahi 2015), WAPA (Asan River, see Raikow and Farahi 2014b), and HALE (Alelele Stream, Palikea Stream, Pipiwai Stream, see Raikow and Farahi 2016). Data on Hawaiian streams was extracted from the National Water Quality Monitoring Council Water Quality Portal, accessed January 2023. Contributing organizations to the Water Quality Portal include the Agricultural Research Service's Sustaining the Earth's Watersheds-Agricultural Research Data System (STEWARDS) database, the Environmental Protection 's Water Quality Exchange (WQX) database and the United States Geological Survey's National Water Information System (NWIS) database.

## Results

### Water Quality Summary

**Total Dissolved Phosphorus:** TDP ranged from 17–75 µg/L but remained near 40µg/L for most of the study period (Table 3, Figures 6–7). Low values were measured at the start of the study period and high values were measured at the end of the study period resulting in a statistically significant temporal trend (Table 4). TDP did not vary seasonally nor spatially.

**Total Dissolved Nitrogen:** TDN ranged from 0.08–0.41 mg/L but was generally observed between 0.10 to 0.20 mg/L. More high outlying measurements were observed toward the end of the study period than the beginning (Figure 7). TDN displayed a weak temporal trend (Table 4) and seasonality by being slightly higher in the wet season (Figure 10). TDN decreased downstream (Figures 11–12).

**$\text{NO}_3^- + \text{NO}_2^-$ :** Nitrate + nitrite ranged from 0.049–0.271 mg/L but was generally observed near 0.125 mg/L. 2017 differed from other years by being more variable, as shown by numerous high and low outliers (Figure 7). TDN displayed a weak temporal trend (Table 4) and displayed strong seasonality by being higher in the wet season (Figure 10). Nitrate + nitrite decreased downstream.

**Chlorophyll:** Chlorophyll was very low across the study period, but became more variable over time, as illustrated by an increasing number of outlying observations (Figure 7). Chlorophyll did not display a temporal trend, nor did it display a spatial pattern (Table 5).

**Oxygen:** Oxygen concentration and saturation were stable across the study period, ranging from 8.5–10.2 mg/L and 90.5%–114 %, respectively. Oxygen showed a weak seasonal pattern of slightly lower saturation and slightly higher concentration in the wet season (Figure 10). Oxygen did not display a temporal trend. Oxygen increased slightly downstream (Figure 11).

**pH:** While pH ranged from 6.2–8.8 most observations centered around 7.8. This parameter did not display a temporal trend but was slightly lower during the wet season (Figure 10). In upstream reaches pH was more highly variable than downstream reaches (Figure 11).

**Specific Conductivity:** Specific conductivity was extremely low, ranging from 0.05 to 0.34 mS/cm (Table 3). A temporal trend of increasing conductivity was observed driven by high outliers observed near the end of the study period (Figure 6). Specific conductivity did not display seasonality but increased downstream (Figure 11).

**Temperature:** Temperature ranged from 16.8–22.6 °C (Table 3). Temperature displayed strong seasonality peaking in the third quarter of the year (Figure 9) and being cooler in the rainy season (Figure 10). No temporal trend was observed. Temperature was lower in upper reaches of the stream, then remained consistent below FKALA04 (at ~3500m from the mouth, Figure 11).

**Turbidity:** Waters were very clear with nearly all turbidity observations at or near 0.1 FNU (Table 3). No seasonality or temporal trends were observed (Table 5). Turbidity did not vary spatially. Turbidity did not display a temporal trend.

**Table 3.** Ranges of water quality parameters in Waikolu Stream, Kalaupapa National Historical Park, Moloka'i, Hawaii 2007–2017.

| Parameter                                                   | Unit  | n   | Maximum | 3 <sup>rd</sup><br>Quartile | Mean  | Median | 1 <sup>st</sup><br>Quartile | Minimum |
|-------------------------------------------------------------|-------|-----|---------|-----------------------------|-------|--------|-----------------------------|---------|
| TDP                                                         | ug/L  | 257 | 75.3    | 45.3                        | 41.1  | 40.5   | 36.5                        | 17.3    |
| TDN                                                         | mg/L  | 266 | 0.41    | 0.18                        | 0.16  | 0.15   | 0.13                        | 0.08    |
| NO <sub>3</sub> <sup>-</sup> + NO <sub>2</sub> <sup>-</sup> | mg/L  | 258 | 0.27    | 0.15                        | 0.13  | 0.13   | 0.10                        | 0.05    |
| Chlorophyll                                                 | ug/L  | 233 | 18.92   | 1.07                        | 1.19  | 0.32   | 0.1                         | 0.02    |
| ODO Conc                                                    | mg/L  | 289 | 10.2    | 9.32                        | 9.18  | 9.21   | 9.03                        | 8.48    |
| ODO Sat                                                     | %     | 289 | 113.6   | 101.9                       | 100.7 | 101.1  | 99.7                        | 90.5    |
| pH                                                          | –     | 270 | 8.77    | 8.02                        | 7.76  | 7.83   | 7.52                        | 6.24    |
| Salinity                                                    | ppt   | 288 | 0.16    | 0.06                        | 0.06  | 0.06   | 0.05                        | 0.02    |
| SpC                                                         | mS/cm | 288 | 0.34    | 0.12                        | 0.12  | 0.12   | 0.1                         | 0.05    |
| Temp                                                        | C     | 295 | 22.6    | 20.5                        | 19.9  | 19.8   | 19.2                        | 16.8    |
| Turbidity                                                   | FNU   | 253 | 14.24   | 0.1                         | 0.26  | 0.1    | 0.1                         | 0.1     |

### Temporal Trends

Temporal trends were detected across the 2007–2017 study period for TDN (increasing trend), TDP (increasing trend), and specific conductance (increasing trend, Tables 4–5, Figures 6–7).

**Table 4.** Trend analysis of water quality parameters in Waikolu Stream, Kalaupapa National Historical Park, Moloka'i, Hawaii 2007–2017.

| Parameter | Term                  | Estimate | Std. Error | df      | t value | p            |
|-----------|-----------------------|----------|------------|---------|---------|--------------|
| NO3       | (Intercept)           | 0.087    | 0.021      | 1.832   | 4.129   | 0.06         |
|           | Time <sup>1</sup>     | 0.001    | 0.002      | 10.12   | 0.615   | 0.55         |
|           | Distance <sup>2</sup> | 0        | 0          | 110.645 | 7.946   | (p < 0.0001) |
| TDN       | (Intercept)           | 0.096    | 0.016      | 2.118   | 5.952   | (p < 0.05)   |
|           | Time <sup>1</sup>     | 0.003    | 0.001      | 9.14    | 2.691   | (p < 0.05)   |
|           | Distance <sup>2</sup> | 0        | 0          | 99.055  | 7.336   | (p < 0.0001) |
| TDP       | (Intercept)           | 0.031    | 0.003      | 14.081  | 12.233  | (p < 0.0001) |
|           | Time <sup>1</sup>     | 0.001    | 0          | 9.356   | 3.325   | (p < 0.01)   |
|           | Distance <sup>2</sup> | 0        | 0          | 117.378 | 0.413   | 0.68         |

<sup>1</sup> Time is the parameter evaluating temporal trend.

<sup>2</sup> Distance to stream mouth

**Table 4 (continued).** Trend analysis of water quality parameters in Waikolu Stream, Kalaupapa National Historical Park, Moloka'i, Hawaii 2007–2017.

| Parameter | Term                  | Estimate | Std. Error | df      | t value | p            |
|-----------|-----------------------|----------|------------|---------|---------|--------------|
| ODOConc   | (Intercept)           | 2.322    | 0.009      | 9.965   | 263.48  | (p < 0.0001) |
|           | Time <sup>1</sup>     | 0.001    | 0.001      | 7.993   | 0.393   | 0.70         |
|           | Distance <sup>2</sup> | 0        | 0          | 32.081  | -2.637  | (p < 0.05)   |
| ODOSat    | (Intercept)           | 4.637    | 0.009      | 2.976   | 495.082 | (p < 0.0001) |
|           | Time <sup>1</sup>     | 0        | 0.001      | 6.539   | 0.479   | 0.65         |
|           | Distance <sup>2</sup> | 0        | 0          | 121.02  | -7.022  | (p < 0.0001) |
| pH        | (Intercept)           | 2.151    | 0.021      | 10.668  | 102.398 | (p < 0.0001) |
|           | Time <sup>1</sup>     | 0.005    | 0.003      | 10.904  | 1.668   | 0.12         |
|           | Distance <sup>2</sup> | 0        | 0          | 23.664  | -3.745  | (p < 0.01)   |
| Temp      | (Intercept)           | 3.073    | 0.027      | 2.103   | 114.944 | (p < 0.0001) |
|           | Time <sup>1</sup>     | -0.001   | 0.002      | 9.273   | -0.47   | 0.65         |
|           | Distance <sup>2</sup> | 0        | 0          | 91.662  | -6.792  | (p < 0.0001) |
| SpC       | (Intercept)           | 0.091    | 0.01       | 12.417  | 9.456   | (p < 0.0001) |
|           | Time <sup>1</sup>     | 0.006    | 0.001      | 9.429   | 4.529   | (p < 0.01)   |
|           | Distance <sup>2</sup> | 0        | 0          | 276.732 | -5.746  | (p < 0.0001) |

<sup>1</sup> Time is the parameter evaluating temporal trend.

<sup>2</sup> Distance to stream mouth

**Table 5.** Trend analysis using the seasonal Mann Kendall Test of water quality parameters in Waikolu Stream, Kalaupapa National Historical Park, Moloka'i, Hawaii 2007–2017.

| Parameter   | Tau   | Slope  | Intercept | p    |
|-------------|-------|--------|-----------|------|
| Chlorophyll | -0.09 | -0.004 | -101.7    | 0.58 |
| Turbidity   | -0.1  | 0      | 0.1       | 0.16 |

## Evaluation of State Water Quality Compliance

For three quarters TP and TN were collected and compared to State of Hawaii water quality standards (Table 2) including both wet and dry seasons. Geometric means for TN did not exceed state standards in 2014 and 2015 (Table 6). Geometric means for TP exceeded state standards in the dry seasons of 2014 and 2015, but not the wet season in 2015 (Table 6). Turbidity never exceeded state standards (Table 7). Nitrate + Nitrite ( $\text{NO}_3^- + \text{NO}_2^-$ ) exceeded state standards during all sampling events (Table 7).

**Table 6.** Ranges of Total Phosphorus (TP) and Total Nitrogen (TN) in Waikolu Stream by season, Kalaupapa National Historical Park, Moloka'i, Hawaii 2014–2015.

| Nutrient | Year | Season | Unit | n  | Max  | 3 <sup>rd</sup><br>Quartile | Mean | Median | 1 <sup>st</sup><br>Quartile | Minimum | Geometric<br>Mean | Ex. <sup>1</sup> |
|----------|------|--------|------|----|------|-----------------------------|------|--------|-----------------------------|---------|-------------------|------------------|
| TP       | 2014 | Dry    | ug/L | 16 | 51   | 47                          | 41   | 45     | 33                          | 29      | 41                | –                |
| TP       | 2015 | Dry    | ug/L | 8  | 43   | 42                          | 39   | 41     | 37                          | 33      | 39                | (p < 0.05)       |
| TP       | 2015 | Wet    | ug/L | 16 | 49   | 45                          | 43   | 44     | 41                          | 35      | 43                | –                |
| TN       | 2014 | Dry    | mg/L | 16 | 0.22 | 0.19                        | 0.15 | 0.15   | 0.12                        | 0.09    | 0.15              | –                |
| TN       | 2015 | Dry    | mg/L | 8  | 0.21 | 0.19                        | 0.16 | 0.17   | 0.14                        | 0.10    | 0.16              | –                |
| TN       | 2015 | Wet    | mg/L | 16 | 0.30 | 0.22                        | 0.19 | 0.17   | 0.16                        | 0.13    | 0.19              | –                |

<sup>1</sup> Exceedance of state standards

**Table 7.** Geometric means of  $\text{NO}_3^- + \text{NO}_2^-$  and turbidity in Waikolu Stream by season, Kalaupapa National Historical Park, Moloka'i, Hawaii.

| Season | Year | $\text{NO}_3^- + \text{NO}_2^-$<br>(n) | $\text{NO}_3^- + \text{NO}_2^-$<br>(mg/L, Geometric<br>mean) | Turbidity<br>(n) | Turbidity<br>(NTU, Geometric<br>mean) |
|--------|------|----------------------------------------|--------------------------------------------------------------|------------------|---------------------------------------|
| dry    | 2008 | 8                                      | 0.117                                                        | 7                | 0.11                                  |
| dry    | 2009 | 16                                     | 0.102                                                        | 23               | 0.10                                  |
| dry    | 2010 | 9                                      | 0.113                                                        | 17               | 0.16                                  |
| dry    | 2011 | 16                                     | 0.109                                                        | 22               | 0.15                                  |
| dry    | 2012 | 15                                     | 0.086                                                        | 14               | 0.14                                  |
| dry    | 2013 | 16                                     | 0.077                                                        | 13               | 0.23                                  |
| dry    | 2014 | 16                                     | 0.104                                                        | 8                | 0.10                                  |
| dry    | 2015 | 8                                      | 0.128                                                        | 8                | 0.13                                  |
| dry    | 2016 | 16                                     | 0.123                                                        | 16               | 0.14                                  |
| dry    | 2017 | 12                                     | 0.116                                                        | 16               | 0.10                                  |
| wet    | 2007 | 7                                      | 0.093                                                        | 1                | 1.30                                  |
| wet    | 2008 | 8                                      | 0.161                                                        | 7                | 0.11                                  |
| wet    | 2009 | 8                                      | 0.126                                                        | 8                | 0.18                                  |
| wet    | 2010 | 8                                      | 0.171                                                        | 16               | 0.14                                  |
| wet    | 2011 | 16                                     | 0.139                                                        | 14               | 0.14                                  |
| wet    | 2012 | 8                                      | 0.129                                                        | 8                | 0.10                                  |
| wet    | 2013 | 16                                     | 0.125                                                        | 7                | 0.11                                  |
| wet    | 2015 | 16                                     | 0.159                                                        | 8                | 0.10                                  |
| wet    | 2016 | 16                                     | 0.161                                                        | 16               | 0.10                                  |
| wet    | 2017 | 24                                     | 0.136                                                        | 24               | 0.10                                  |

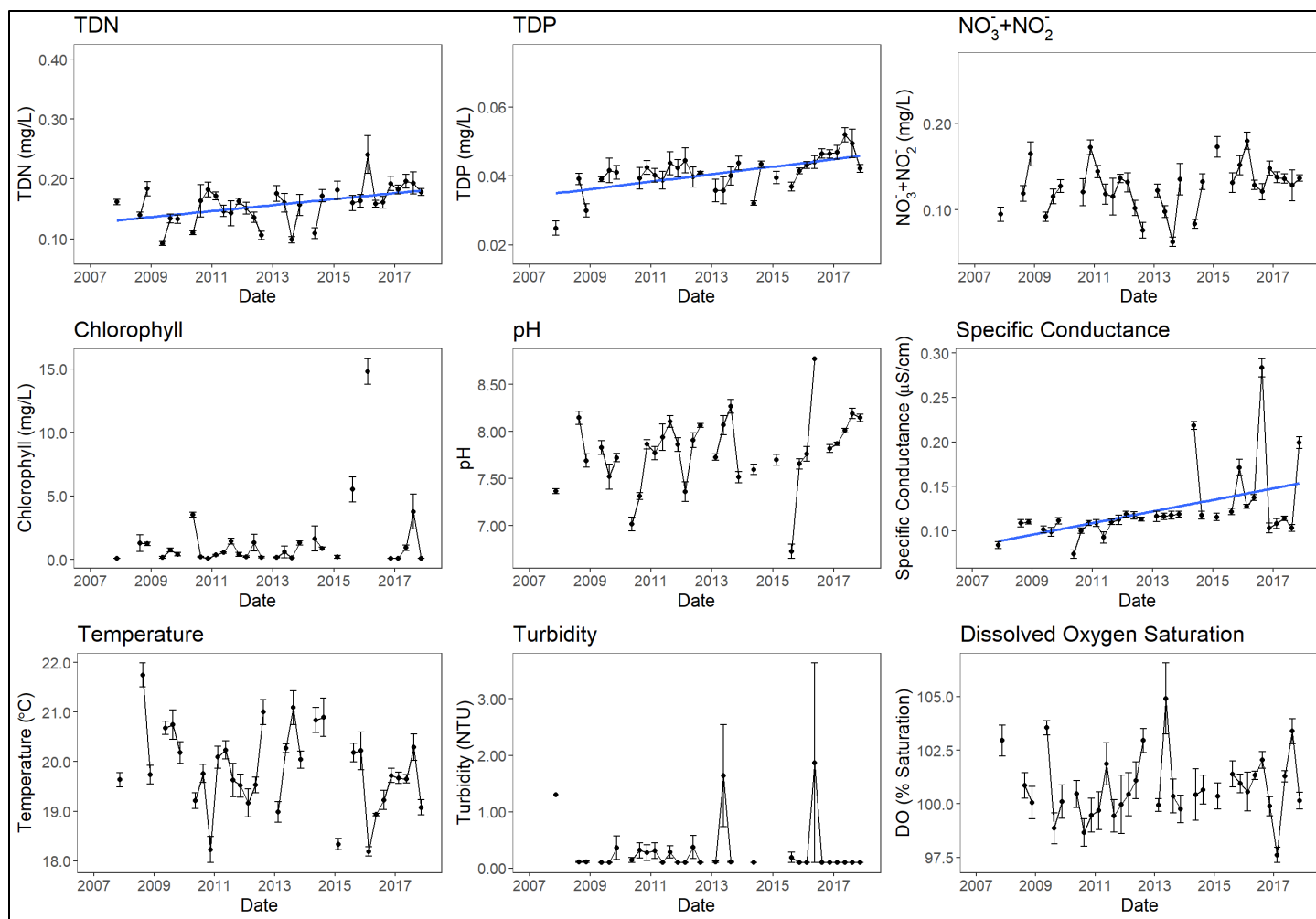


**Figure 6.** Water quality parameters in Waikolu Stream, Kalapapa National Historical Park, Moloka'i, Hawaii, 2007–2017. Linear regressions are presented where trends were detected (as tabulated in table 4).

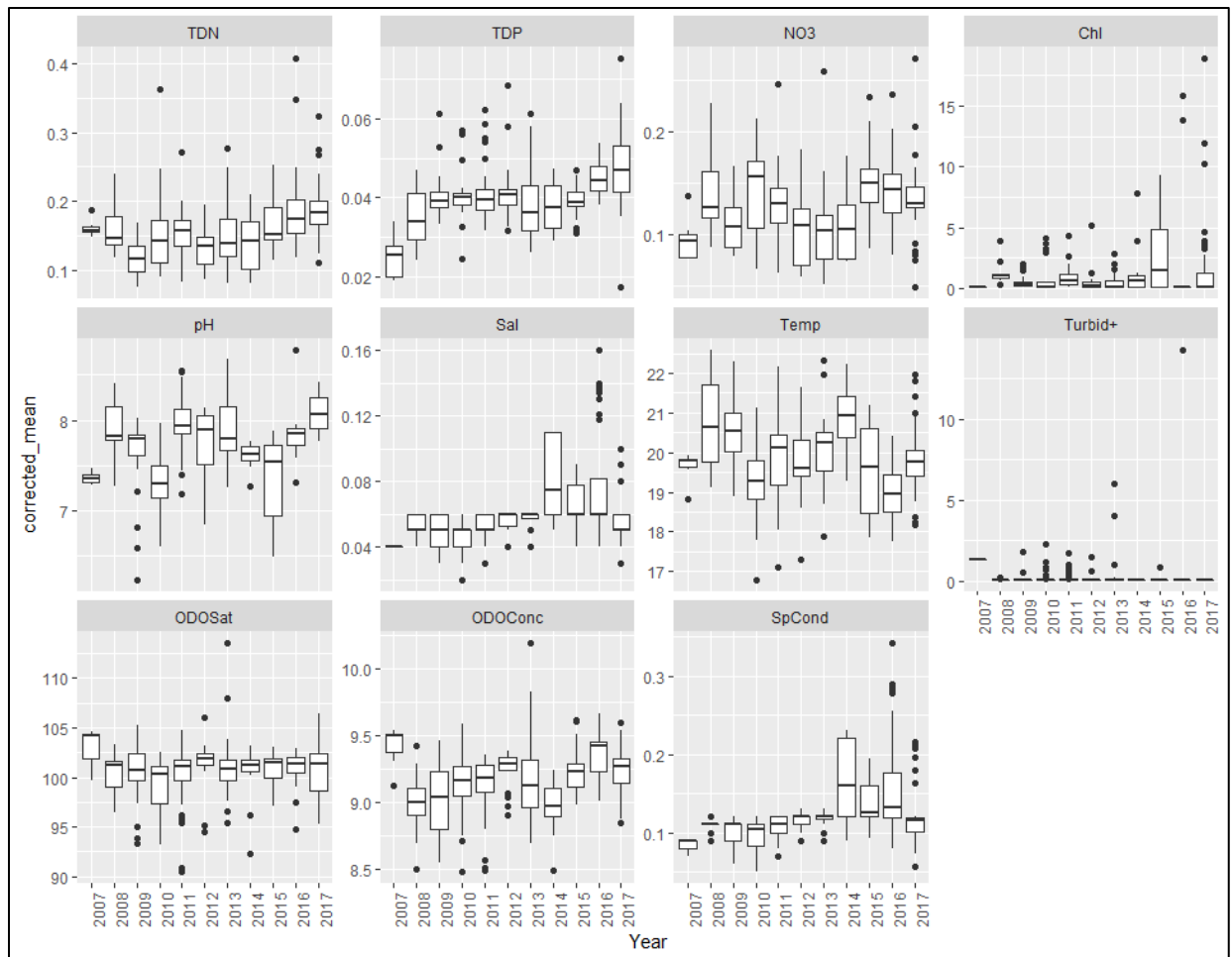


**Figure 7.** Distributions of water quality parameters by year in Waikolu Stream, Kalaupapa National Historical Park, Moloka'i, Hawaii, 2007–2017. Units: TDN (mg/L), TDP (mg/L), NO<sub>2</sub><sup>-</sup>+NO<sub>3</sub><sup>-</sup> (mg/L), Chlorophyll (mg/L), pH (none), Salinity (ppt), Temperature (°C), Turbidity (NTU), Optical Dissolved Oxygen Saturation (%), Optical Dissolved Oxygen Concentration (mg/L), Specific Conductance (mS/cm).

### Dissolved and Particulate Nutrient Fractions

The waters of Waikolu Stream were dominated by dissolved fractions of phosphorus and nitrogen (Table 8). Both phosphorus and nitrogen showed median dissolved fractions of 90% (Figure 8).

**Table 8.** Summary of the distribution of dissolved nutrient proportions (%) of phosphorus (P) and nitrogen (N) in waters of Waikolu Stream, Kalaupapa National Historical Park, Moloka'i, Hawaii.

| Statistic                | P     | N     |
|--------------------------|-------|-------|
| Maximum                  | 100 * | 100 * |
| 3 <sup>rd</sup> Quartile | 94    | 98    |
| Mean                     | 90    | 90    |
| Median                   | 90    | 90    |
| 1 <sup>st</sup> Quartile | 86    | 80    |
| Minimum                  | 68    | 34    |

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

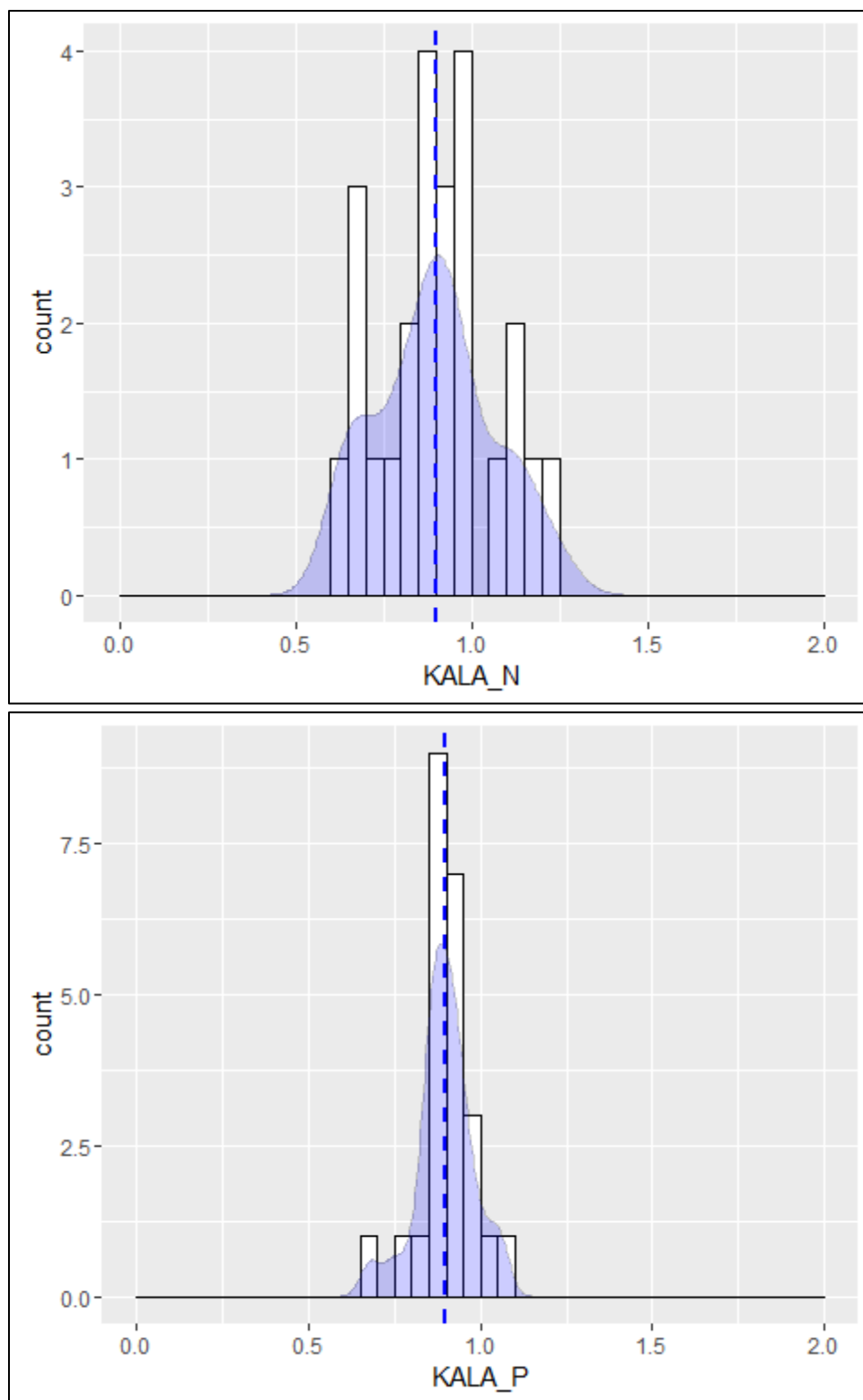


**Figure 8.** Proportions of dissolved nitrogen (top) and phosphorus (bottom) in Waikolu Stream, Kalaupapa National Historical Park, Moloka'i, Hawaii.

## Seasonality

Seasonality was observed in several water quality parameters (Table 9, Figures 9–10). TDN and  $\text{NO}_3^- + \text{NO}_2^-$  showed slightly higher concentrations in the wet season. Differences in chlorophyll and pH between seasons were very slight, with the wet season showing slightly lower concentrations. Variation in oxygen concentration and thus saturation between seasons were also very small with saturation decreasing slightly in the wet season. Specific conductance increased slightly in the wet season. Temperature was lower in the wet season. Seasonality was not observed in TDP and turbidity.

**Table 9.** Summary of quarter and wet/dry seasonality tests showing p-values.

| Parameter                       | Quarter seasonality tests |              |              |            |              |              | Wet/Dry seasonality tests |              |              |              |
|---------------------------------|---------------------------|--------------|--------------|------------|--------------|--------------|---------------------------|--------------|--------------|--------------|
|                                 | R <sup>2</sup>            | Main         | Time         | Q1         | Q2           | Q3           | R <sup>2</sup>            | Main         | Time         | Wet          |
| TDN                             | 0.20                      | (p < 0.0001) | (p < 0.0001) | 0.31       | (p < 0.0001) | (p < 0.01)   | 0.19                      | (p < 0.0001) | (p < 0.0001) | (p < 0.0001) |
| TDP                             | 0.15                      | (p < 0.0001) | (p < 0.0001) | 0.70       | 0.86         | 0.08         | 0.14                      | (p < 0.0001) | (p < 0.0001) | 0.88         |
| $\text{NO}_3^- + \text{NO}_2^-$ | 0.20                      | (p < 0.0001) | (p < 0.001)  | 0.53       | (p < 0.0001) | (p < 0.0001) | 0.20                      | (p < 0.0001) | (p < 0.05)   | (p < 0.0001) |
| Chlorophyll                     | 0.08                      | (p < 0.001)  | (p < 0.05)   | 0.54       | (p < 0.05)   | (p < 0.01)   | 0.04                      | (p < 0.01)   | (p < 0.05)   | (p < 0.01)   |
| pH                              | 0.05                      | (p < 0.01)   | (p < 0.0001) | 0.22       | 0.63         | 0.61         | 0.07                      | 0.08         | (p < 0.0001) | (p < 0.01)   |
| ODOsat                          | 0.07                      | (p < 0.001)  | (p < 0.05)   | 0.13       | (p < 0.01)   | 0.46         | 0.04                      | (p < 0.01)   | 0.05         | (p < 0.01)   |
| SpC                             | 0.19                      | (p < 0.0001) | (p < 0.0001) | (p < 0.05) | 0.32         | 0.25         | 0.19                      | (p < 0.0001) | (p < 0.0001) | 0.06         |
| Temperature                     | 0.19                      | (p < 0.0001) | (p < 0.05)   | (p < 0.05) | (p < 0.05)   | (p < 0.0001) | 0.18                      | (p < 0.0001) | (p < 0.01)   | (p < 0.0001) |
| Turbidity                       | 0.01                      | 0.17         | 0.31         | 0.71       | 0.10         | 0.83         | 0.002                     | 0.27         | 0.40         | 0.21         |

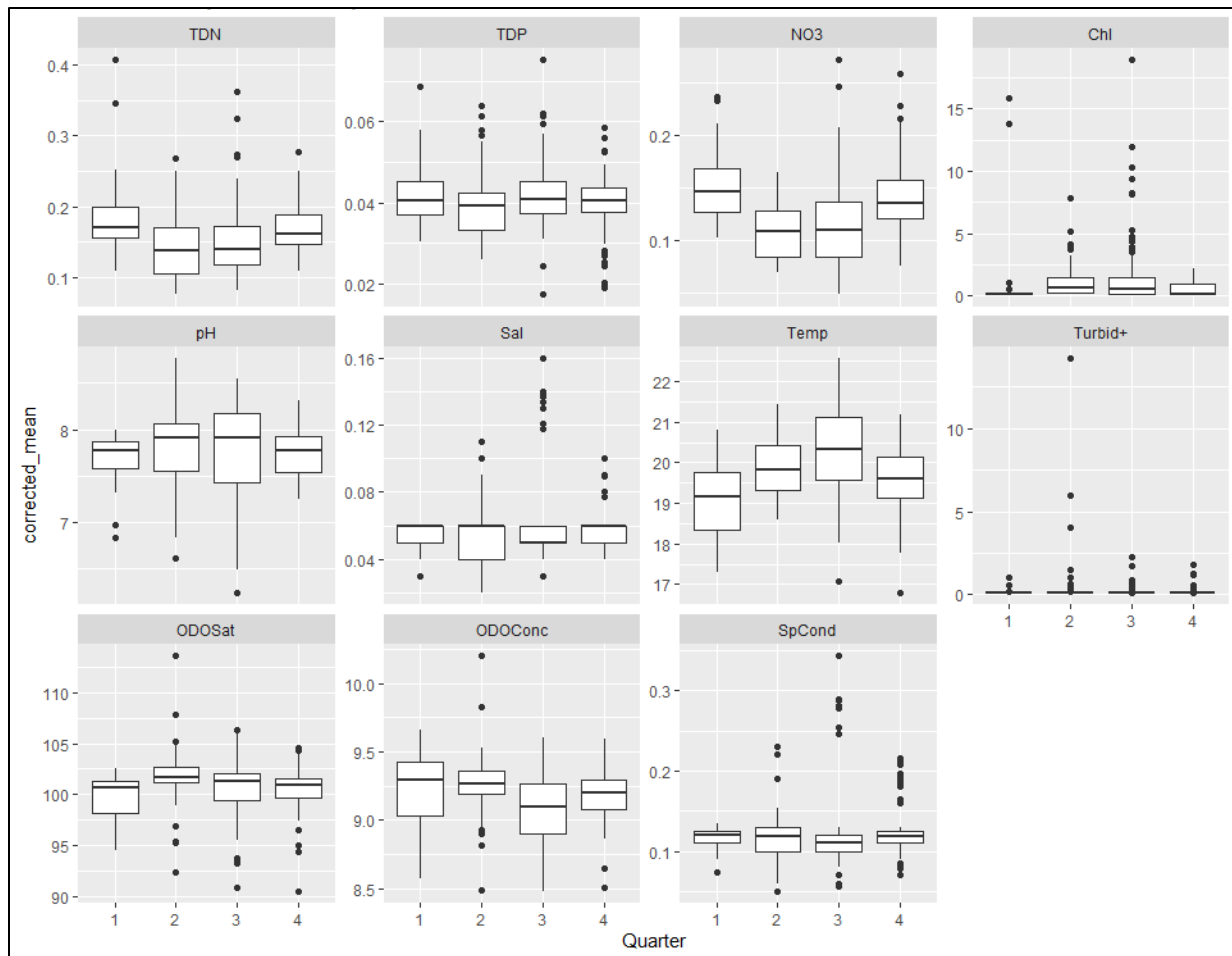


**Figure 9.** Distributions of water quality parameters within quarters from 2007–2017 in Waikolu Stream, Kalaupapa National Historical Park. Units: TDN (mg/L), TDP (mg/L), NO<sub>2</sub>+NO<sub>3</sub> (mg/L), Chlorophyll (mg/L), pH (none), Salinity (ppt), Temperature (°C), Turbidity (NTU), Optical Dissolved Oxygen Saturation (%), Optical Dissolved Oxygen Concentration (mg/L), Specific Conductance (mS/cm).

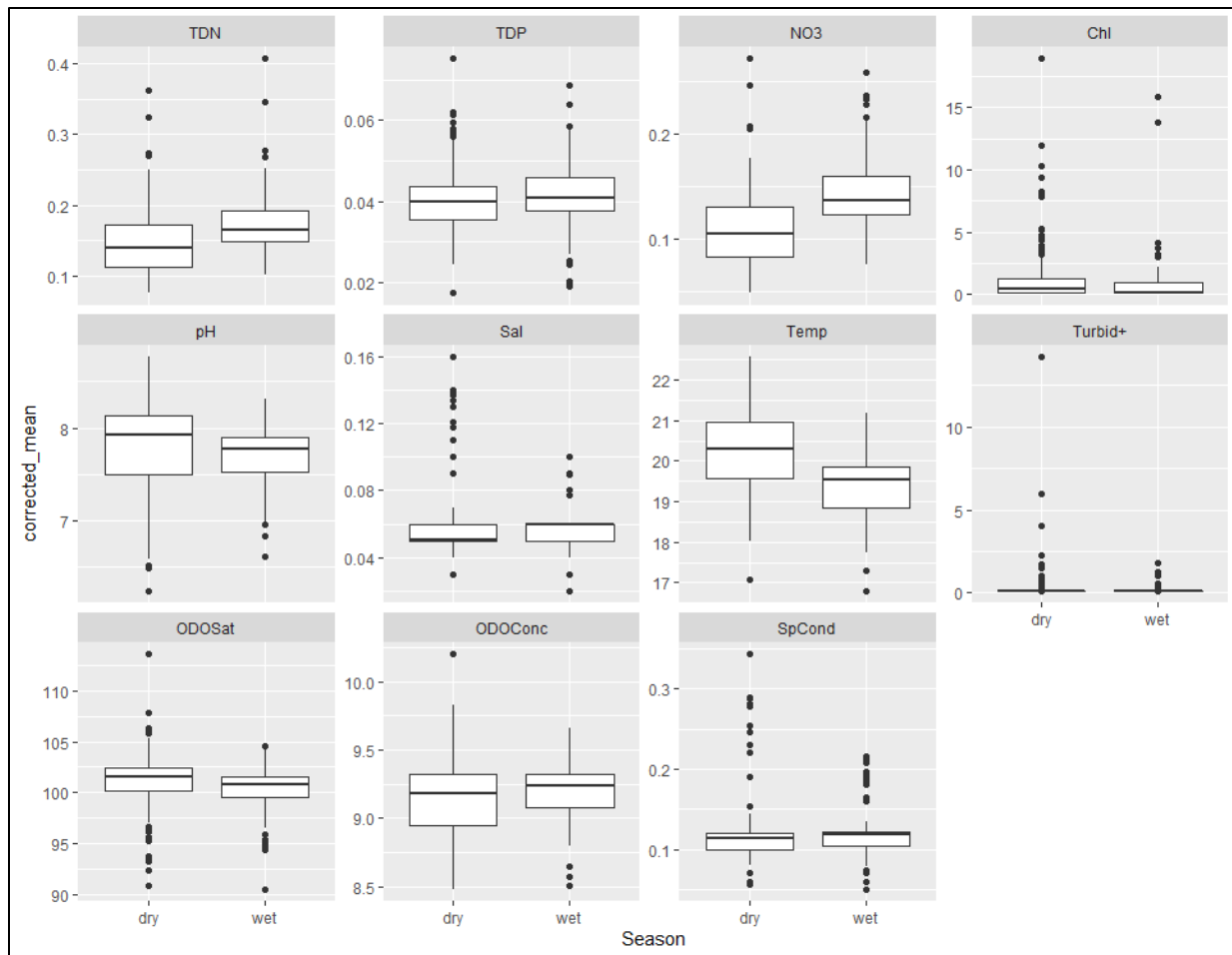


**Figure 10.** Distributions of water quality parameters within wet and dry seasons from 2007–2017 in Waikolu Stream, Kalaupapa National Historical Park. Units: TDN (mg/L), TDP (mg/L), NO<sub>2</sub>+NO<sub>3</sub> (mg/L), Chlorophyll (mg/L), pH (none), Salinity (ppt), Temperature (°C), Turbidity (NTU), Optical Dissolved Oxygen Saturation (%), Optical Dissolved Oxygen Concentration (mg/L), Specific Conductance (mS/cm).

## Spatial water quality patterns

All water quality parameters except TDP, chlorophyll, and turbidity changed with distance from the stream mouth (Tables 10–11, Figure 11). Sampling of upper reaches upstream >3500m from the mouth, or upstream of FKALA04, occurred with less regularity than downstream reaches, and a separate longitudinal analysis is presented for the downstream section (Table 10). TDN and  $\text{NO}_3^- + \text{NO}_2^-$  decreased downstream across the full stream length (Table 10, Figure 11). A slight increase in TDN occurred ~2500m upstream from the mouth near site FKALA07 but this parameter was less variable in lower downstream sections (Figure 11). TDP was also less variable and did not display a changing mean with distance (Figure 10). Chlorophyll did not vary greatly with distance, but a single high measurement at the uppermost site influenced the regression (Figure 11). pH was more variable in upper reaches, which also displayed a decrease at ~3500m upstream of the mouth, just below a confluence with a large tributary (Figure 11). Specific conductance, and thus also salinity, increased downstream. Temperature increased downstream by displaying lower values in upper reaches then generally leveling out below 2500m upstream of the mouth. Oxygen increased downstream and was lower in upper reaches greater than 3500m upstream of the mouth and then generally leveling (Figure 11). Turbidity was not related to distance.

**Table 10.** Linear regression with distance from stream mouth.

| Stream Reach       | Parameter | Term              | Estimate | std. error | Statistic            | p    |
|--------------------|-----------|-------------------|----------|------------|----------------------|------|
| Entire             | TDN       | Distance to mouth | 0        | 0          | 6.804 (p < 0.0001)   |      |
| Entire             | TDP       | Distance to mouth | 0        | 0          | -0.295               | 0.77 |
| Entire             | NO3       | Distance to mouth | 0        | 0          | 7.093 (p < 0.0001)   |      |
| Entire             | pH        | Distance to mouth | 0        | 0          | -3.031 (p < 0.01)    |      |
| Entire             | Sal       | Distance to mouth | 0        | 0          | -9.996 (p < 0.0001)  |      |
| Entire             | Temp      | Distance to mouth | 0        | 0          | -6.463 (p < 0.0001)  |      |
| Entire             | ODOSat    | Distance to mouth | -0.001   | 0          | -7.581 (p < 0.0001)  |      |
| Entire             | ODOConc   | Distance to mouth | 0        | 0          | -2.443 (p < 0.05)    |      |
| Entire             | SpCond    | Distance to mouth | 0        | 0          | -11.387 (p < 0.0001) |      |
| Lower <sup>1</sup> | TDN       | Distance to mouth | 0        | 0          | 4.447 (p < 0.0001)   |      |
| Lower              | TDP       | Distance to mouth | 0        | 0          | -1.366               | 0.17 |
| Lower              | NO3       | Distance to mouth | 0        | 0          | 7.46 (p < 0.0001)    |      |
| Lower              | pH        | Distance to mouth | 0        | 0          | -3.643 (p < 0.001)   |      |
| Lower              | Sal       | Distance to mouth | 0        | 0          | -5.512 (p < 0.0001)  |      |
| Lower              | Temp      | Distance to mouth | 0        | 0          | -1.834               | 0.07 |
| Lower              | ODOSat    | Distance to mouth | -0.001   | 0          | -6.11 (p < 0.0001)   |      |

<sup>1</sup> Lower stream section only (FKALA04 and below):

**Table 10 (continued).** Linear regression with distance from stream mouth.

| Stream Reach | Parameter | Term              | Estimate | std. error | Statistic | <i>p</i>         |
|--------------|-----------|-------------------|----------|------------|-----------|------------------|
| Lower        | ODOConc   | Distance to mouth | 0        | 0          | -4.857    | ( $p < 0.0001$ ) |
| Lower        | SpCond    | Distance to mouth | 0        | 0          | -6.59     | ( $p < 0.0001$ ) |

<sup>1</sup> Lower stream section only (FKALA04 and below):

**Table 11.** Linear regression based on Kendall Rank.

| Reach              | Parameter   | Measure           | Tau    | slope | intercept | <i>p</i> |
|--------------------|-------------|-------------------|--------|-------|-----------|----------|
| Entire             | Chlorophyll | Distance to mouth | 0.098  | 0     | 0         | 0.10     |
| Entire             | Turbidity   | Distance to mouth | -0.01  | 0     | 0         | 0.78     |
| Lower <sup>1</sup> | Chlorophyll | Distance to mouth | -0.069 | 0     | 0         | 0.28     |
| Lower              | Turbidity   | Distance to mouth | -0.049 | 0     | 0         | 0.18     |

<sup>1</sup> Lower stream section only (FKALA04 and below):

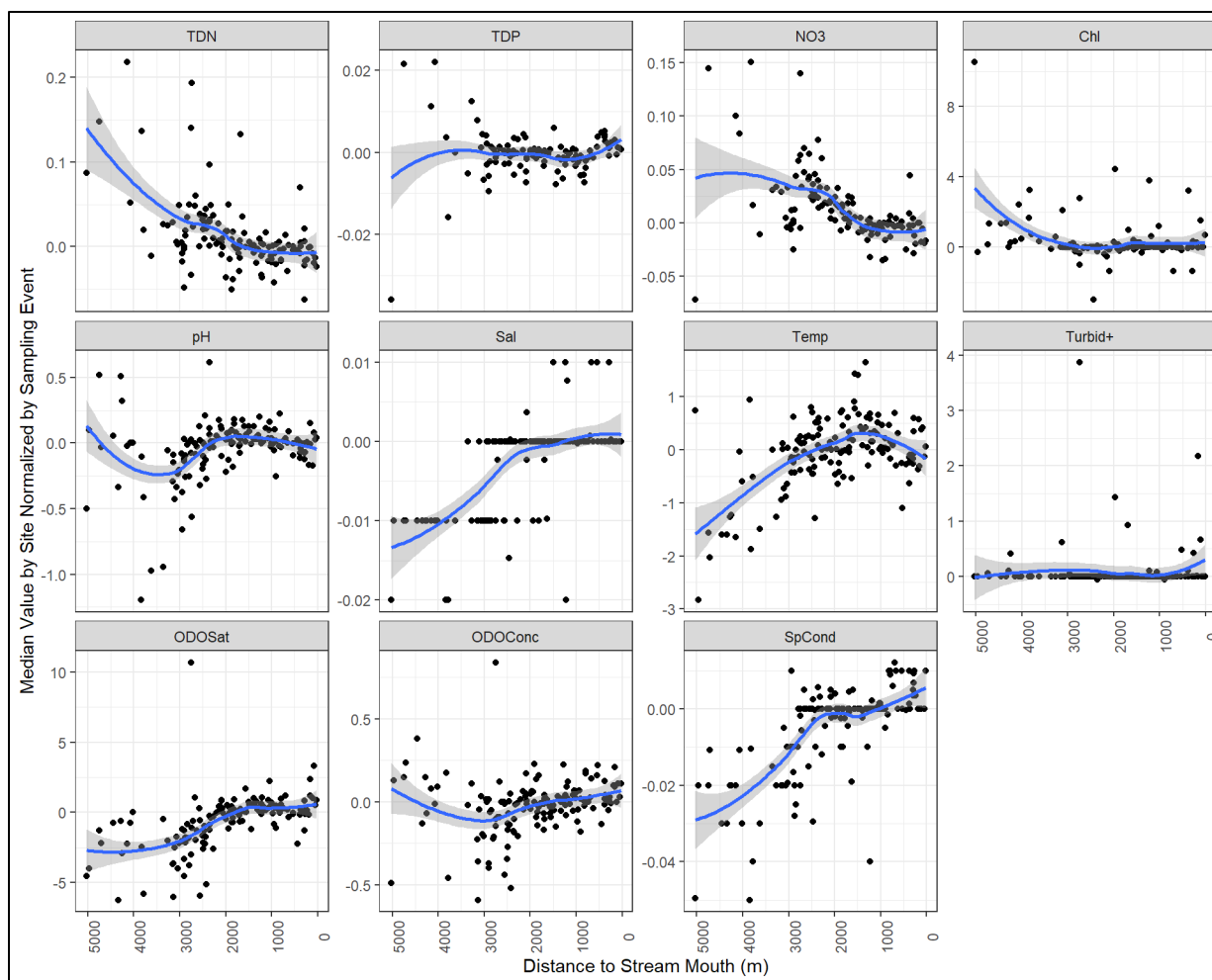


**Figure 11.** Spatial pattern of water quality parameter deviation from the median, normalized to sampling event and fitted with locally estimated scatterplot smoothing (LOESS), 2007–2017, in Waikolu Stream, Kalaupapa National Historical Park. Upstream is to the left of the x-axis and downstream to the right of the x-axis. The 95% confidence interval is indicated in gray. Note that the tunnel diversion occurs at ~3800m.

### Redundant sampling analysis

Water quality parameters as measured at all fixed sites was highly correlated to parameters measured at all temporary sites (Table 12, Figure 12). Water quality parameters measured at FKALA01, FKALA02, or FKALA03 were well correlated with values measured at all other sites, respectively, with FKALA03 yielding the best overall correlation values (median  $R = 0.86$ ) and strongest statistical significance ( $p < 0.0001$  for all parameters, Table 8). Absolute differences between temporal patterns at FKALA03 and data from all other sites was slight (Figure 13). Virtually all correlations involving comparisons of upper stream sites (data grouped from FKALA08, FKALA09, and FKALA10, or “upper” in Table 12) to the rest of the stream were not statistically significant, indicating that values measured at upper sites were not well correlated with values measured at lower sites.

**Table 12.** Correlations of selected water quality parameters between selected sites in Waikolu Stream, Kalaupapa National Historical Park, Moloka'i, Hawaii.

| Parameter                                                   | Fixed vs.<br>Temporary |              | FKALA01 vs<br>all others |              | FKALA02 vs<br>all others |              | FKALA03 vs<br>all others |              | FKALA04 vs<br>all others |              | FKALA01 vs<br>upper <sup>2</sup> |            | FKALA02 vs<br>upper <sup>2</sup> |      | FKALA03 vs<br>upper <sup>2</sup> |             | FKALA04 vs<br>upper <sup>2</sup> |            | Upper <sup>2</sup> vs<br>all others |      |
|-------------------------------------------------------------|------------------------|--------------|--------------------------|--------------|--------------------------|--------------|--------------------------|--------------|--------------------------|--------------|----------------------------------|------------|----------------------------------|------|----------------------------------|-------------|----------------------------------|------------|-------------------------------------|------|
|                                                             | R                      | p            | R                        | p            | R                        | p            | R                        | p            | R                        | p            | R                                | p          | R                                | p    | R                                | p           | R                                | p          | R                                   | p    |
| TDP                                                         | 0.80                   | (p < 0.0001) | 0.72                     | (p < 0.0001) | 0.64                     | (p < 0.001)  | 0.86                     | (p < 0.0001) | 0.09                     | 0.65         | 1.00                             | –          | 1.00                             | –    | 1.00                             | –           | 1.00                             | –          | 1.00                                | –    |
| TDN                                                         | 0.47                   | (p < 0.01)   | 0.70                     | (p < 0.0001) | 0.70                     | (p < 0.0001) | 0.69                     | (p < 0.0001) | 0.64                     | (p < 0.001)  | 0.69                             | 0.52       | 0.99                             | 0.09 | –0.36                            | 0.77        | 0.99                             | 0.10       | 0.97                                | 0.15 |
| NO <sup>-</sup> <sub>3</sub> + NO <sup>-</sup> <sub>2</sub> | 0.73                   | (p < 0.0001) | 0.82                     | (p < 0.0001) | 0.87                     | (p < 0.0001) | 0.89                     | (p < 0.0001) | 0.74                     | (p < 0.0001) | 0.19                             | 0.88       | –0.65                            | 0.55 | –0.97                            | 0.14        | 0.42                             | 0.72       | –0.04                               | 0.97 |
| Chlorophyll                                                 | 0.90                   | (p < 0.0001) | 0.40                     | 0.05         | 0.56                     | (p < 0.05)   | 0.80                     | (p < 0.0001) | 0.87                     | (p < 0.0001) | –0.46                            | 0.54       | –0.56                            | 0.62 | –0.37                            | 0.63        | 1.00                             | (p < 0.01) | 0.94                                | 0.06 |
| ODOconc                                                     | 0.83                   | (p < 0.0001) | 0.77                     | (p < 0.0001) | 0.83                     | (p < 0.0001) | 0.87                     | (p < 0.0001) | 0.52                     | (p < 0.01)   | 0.89                             | 0.11       | 0.31                             | 0.69 | 0.78                             | 0.22        | 0.25                             | 0.75       | 0.73                                | 0.27 |
| pH                                                          | 0.97                   | (p < 0.0001) | 0.87                     | (p < 0.0001) | 0.96                     | (p < 0.0001) | 0.92                     | (p < 0.0001) | 0.84                     | (p < 0.0001) | 0.42                             | 0.73       | 0.74                             | 0.48 | 0.55                             | 0.63        | 0.98                             | 0.11       | 0.96                                | 0.18 |
| SpC                                                         | 0.98                   | (p < 0.0001) | 0.93                     | (p < 0.0001) | 0.99                     | (p < 0.0001) | 0.93                     | (p < 0.0001) | 0.98                     | (p < 0.0001) | 0.34                             | 0.66       | 0.25                             | 0.75 | –0.01                            | 0.99        | 0.90                             | 0.10       | 0.54                                | 0.47 |
| Temperature                                                 | 0.91                   | (p < 0.0001) | 0.81                     | (p < 0.0001) | 0.82                     | (p < 0.0001) | 0.93                     | (p < 0.0001) | 0.74                     | (p < 0.0001) | 0.99                             | (p < 0.05) | 0.25                             | 0.75 | 1.00                             | (p < 0.001) | 0.81                             | 0.20       | 0.89                                | 0.11 |
| Mean <sup>1</sup>                                           | 0.82                   | –            | 0.75                     | –            | 0.80                     | –            | 0.86                     | –            | 0.68                     | –            | 0.62                             | –          | 0.59                             | –    | 0.63                             | –           | 0.79                             | –          | 0.76                                | –    |
| Median <sup>1</sup>                                         | 0.86                   | –            | 0.79                     | –            | 0.83                     | –            | 0.88                     | –            | 0.74                     | –            | 0.58                             | –          | 0.61                             | –    | 0.67                             | –           | 0.94                             | –          | 0.92                                | –    |

<sup>1</sup> Mean and median using absolute values of R.

<sup>2</sup> Data grouped from sites FKALA08, FKALA09, and FKALA10.

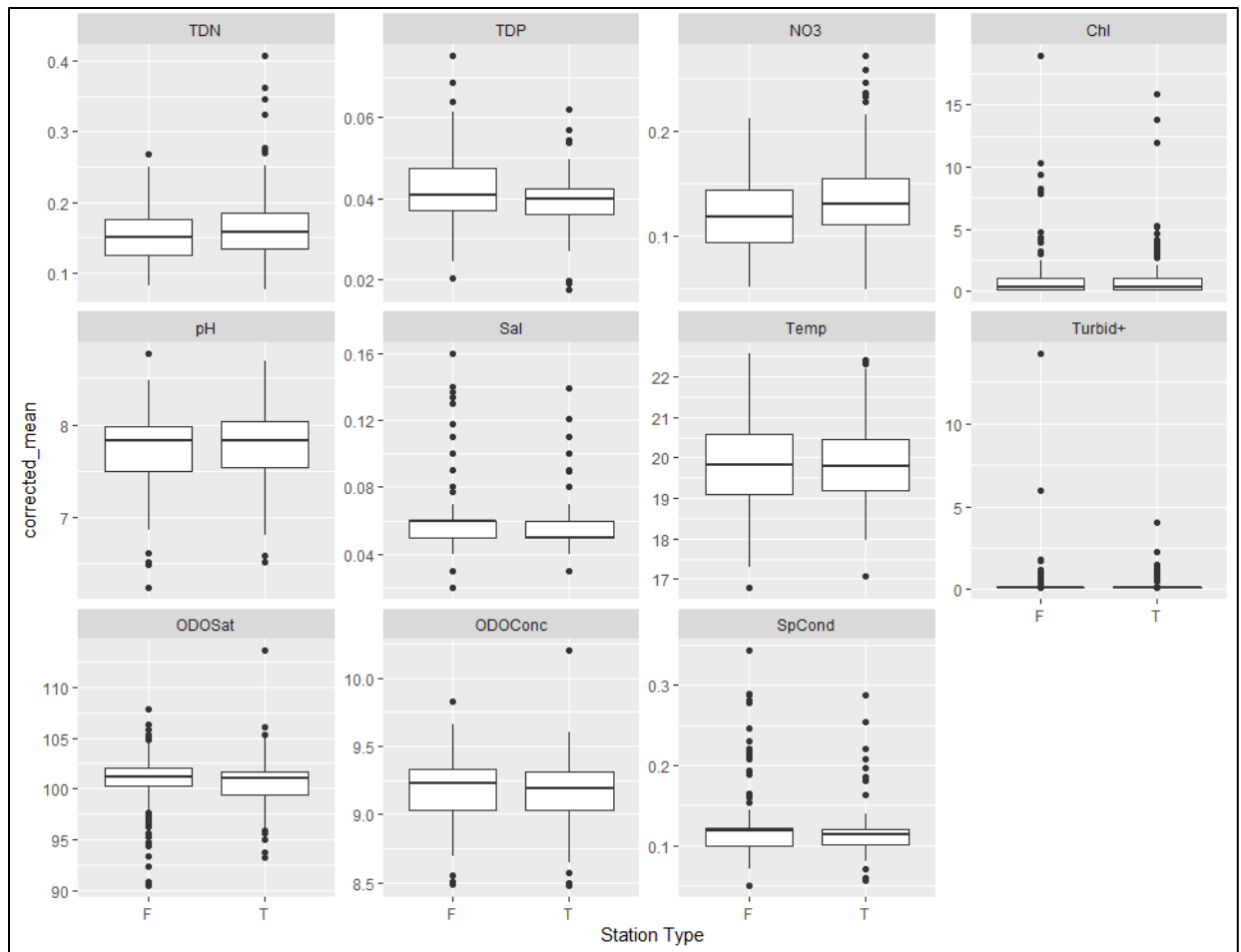


**Figure 12.** Distribution of water quality parameter values measured at fixed sites vs. temporary sites, 2007–2017, in Waikolu Stream, Kalaupapa National Historical Park, Moloka'i, Hawaii. Units: TDN (mg/L), TDP (mg/L), NO<sub>2</sub>+NO<sub>3</sub> (mg/L), Chlorophyll (mg/L), pH (none), Salinity (ppt), Temperature (°C), Turbidity (NTU), Optical Dissolved Oxygen Saturation (%), Optical Dissolved Oxygen Concentration (mg/L), Specific Conductance (mS/cm).

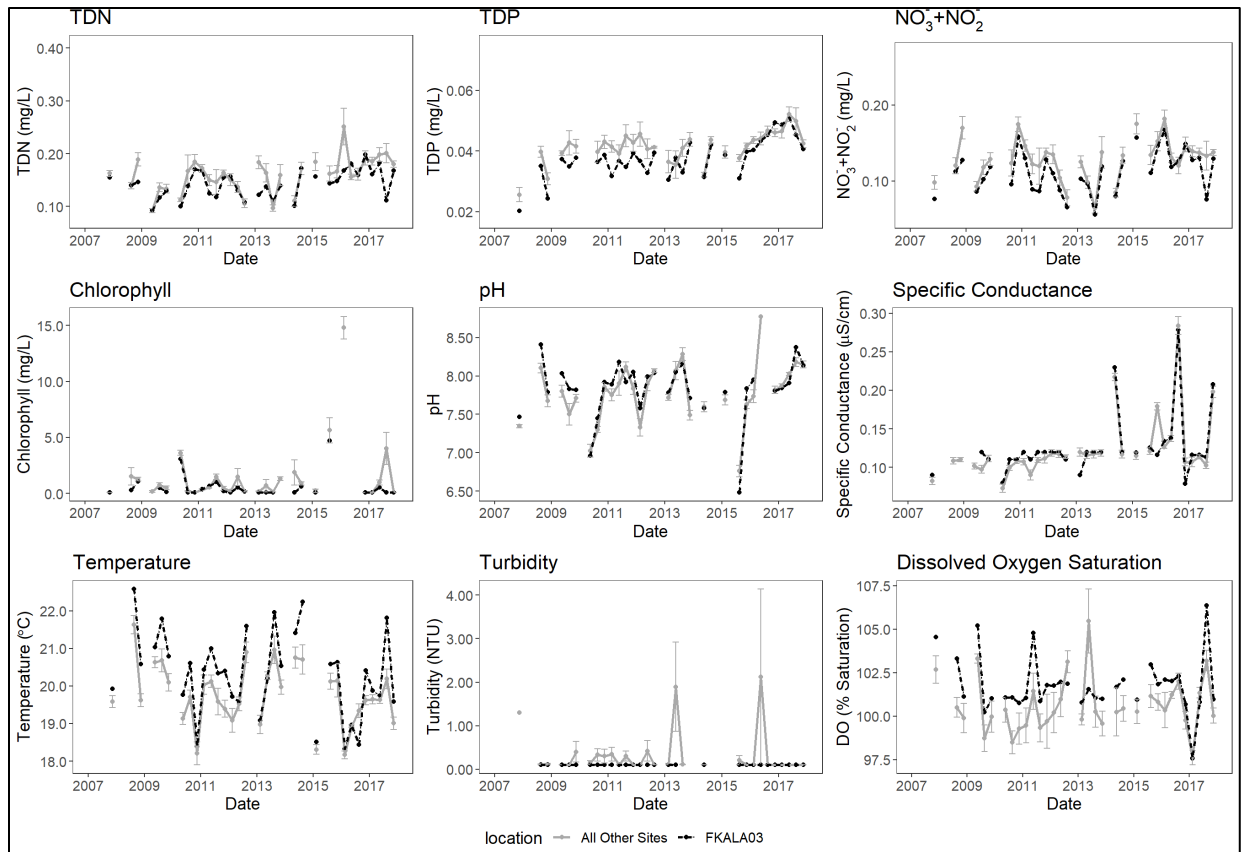


**Figure 13.** Water quality at FKALA03 compared to water quality at all other sites in Waikolu Stream, Kalaupapa National Historical Park, Moloka'i, Hawaii.

## Climate

The NOAA Oceanic Niño Index (ONI) indicates La Niña conditions when values are less than  $-0.5$  and El Niño conditions when values are greater than  $0.5$  (Figure 14). During the study period the following ENSO conditions were present: 2007–2009 was a moderate La Niña, 2010 was a moderate El Niño, 2011–2012 was a moderate La Niña, 2012–2015 were neutral conditions, 2015–2016 was a very strong El Niño, and 2016–2017 was a neutral to weak La Niña. Precipitation data was available for the entire study period from the Makapulapai station, and from 2012–2017 from the Pu’u Ali’i station. The Pu’u Ali’i station mirrored the pattern of the Makapulapai station but recorded much higher precipitation (Figure 14, Simeral and Wasser 2021). The El Niño condition that developed in 2015 caused an increase in rain earlier in the year (see “A” in Figure 14) compared to previous years followed by less rain during the typically wet season (see “B” in Figure 14). 2017 was atypically dry during the dry season under neutral conditions following the very strong 2015 El Niño (see “C” in Figure 14). Temporal patterns did not obviously correspond to changing ENSO conditions, and baseflow conditions were remarkably stable during changing climate conditions.

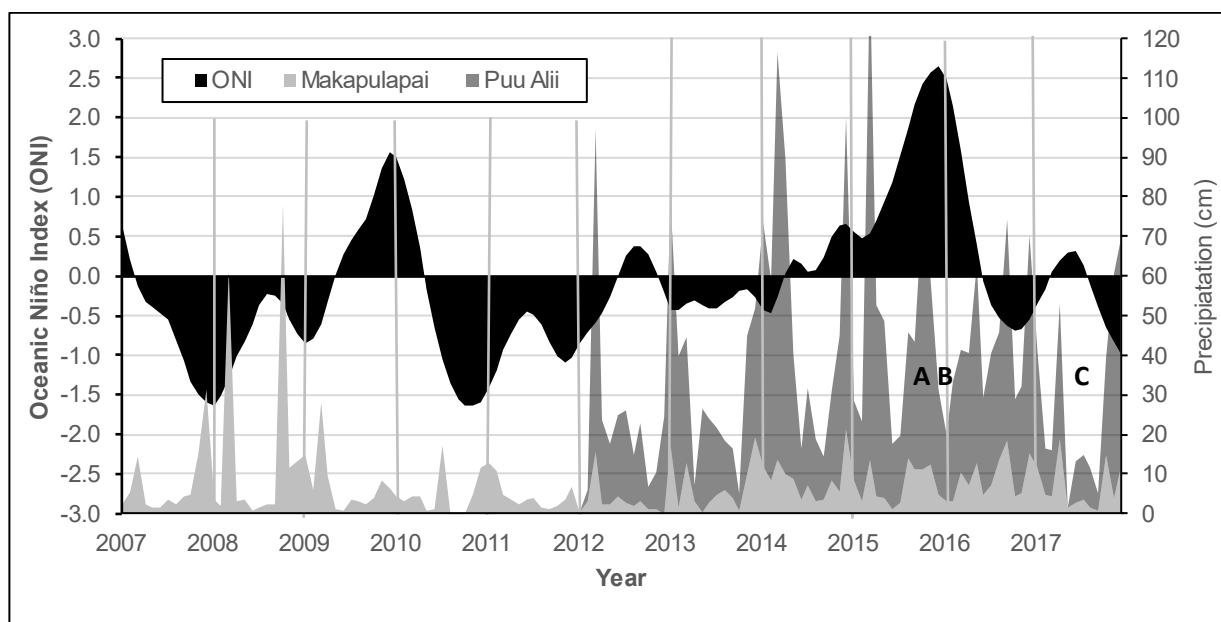


**Figure 14.** Oceanic Niño Index (ONI) and precipitation in Kalaupapa National Historical Park, Moloka‘i, Hawaii. Precipitation data began to be collected at Pu’u Ali’i in 2012.

## Summary of results

- $\text{NO}_3^- + \text{NO}_2^-$  regularly exceeded state water quality criteria.
- TP exceeded state water quality criteria once out of 33 quarters evaluated.
- TDN and TDP concentrations were low, oxygen was high, turbidity was low.
- Conditions were consistent with similar pacific island streams (see discussion).
- Dissolved nutrient fractions dominated typical baseflow conditions, as expected.
- Seasonality was detected for TDN,  $\text{NO}_3^- + \text{NO}_2^-$ , chlorophyll, pH, oxygen, and temperature.

- Several trends were detected; however, the magnitude of change was small.
- Parameters varied spatially to a limited extent with distance along the channel.
- Temporary sites were highly correlated with fixed sites and did not add to trend analysis.
- While subtle spatial patterns were present, site FKALA03 was highly correlated with measurements taken across the entire stream.

## Discussion

### Water Quality

Water quality in Waikolu Stream was generally good with the exception of  $\text{NO}_3^- + \text{NO}_2^-$ . While nutrient concentrations were higher than those measured in the marine portions of Kalaupapa National Historical Park (Raikow et al. 2021), this difference was expected. Streams are known to supply nutrients to nearshore marine habitats, and nutrient levels in Waikolu Stream represent ecological subsidies provided by terrestrial ecosystems to streams and ultimately marine ecosystems. Many water quality parameters in Waikolu Stream were consistent with streams in other well-protected NPS watersheds on Pacific islands including those on Maui, Guam, and American Samoa (Figure 15); specifically with regard to TDN, TDP, chlorophyll, pH, turbidity, SpC, and oxygen. Streams on these widely dispersed islands differed from Waikolu Stream in subtle ways. Waikolu Stream had slightly lower concentrations of TDP than NPSA streams in American Samoa, though this difference was not biologically significant. Waikolu Stream had lower SpC than the Asan River in WAPA on Guam, likely due to differences in the underlying geology in Guam supplying more dissolved minerals. Waikolu stream was similar in temperature to streams in HALE on Maui, and cooler than streams in NPSA and WAPA. Interestingly,  $\text{NO}_3^- + \text{NO}_2^-$  concentrations in Waikolu Stream were higher than those found in streams of other Pacific island national parks (Figure 15), higher than Island of Hawaii streams draining conservation watersheds (Michaud and Weinger 2011) and exceeded state standards (Hawaii 2012).

Michaud and Wiegner (2011) examined 24 streams on the Island of Hawai'i. Streams draining conservation watersheds, and  $\text{NO}_3^- + \text{NO}_2^-$  values ranged from  $<0.001$  to  $0.035$  mg/L, with a watershed described as "half agriculture" displaying  $0.05$  mg/L. Streams draining dominantly agricultural watersheds displayed  $\text{NO}_3^- + \text{NO}_2^-$  ranging from  $0.005$  to  $0.139$  mg/L. Thus, Waikolu Stream displayed  $\text{NO}_3^- + \text{NO}_2^-$  similar to agricultural streams on the windward side of the Island of Hawai'i. Waikolu Stream TDN was consistent with Island of Hawai'i streams draining both conservation and agricultural watersheds, which had similar ranges to each other. On the Island of Hawai'i TDN was dominated by DON ( $54\% \pm 30\%$ ) and  $\text{NO}_3^- + \text{NO}_2^-$  ( $34\% \pm 32\%$ ), while  $\text{NO}_3^- + \text{NO}_2^-$  appeared to make up nearly all TDN in Waikolu Stream, e.g.,  $87\%$  of median TDN. Specific conductivity in Waikolu Stream (median =  $0.12$  mS/cm) was more similar to streams draining dominantly agricultural watersheds on Island of Hawai'i ( $0.09$  to  $0.12$  mS/cm) than streams draining conservation watersheds ( $0.03$  to  $0.09$  mS/cm). Waikolu Stream had considerably more TP in 2014 and 2015 (median =  $41$  to  $45$   $\mu\text{g/L}$ ) than all streams studied on the Island of Hawai'i (mean of all streams =  $8$   $\mu\text{g/L}$ ). Although sampling methods did not exactly match those for evaluation of state water quality standards, data from several Island of Hawai'i streams indicated possible violation of state criteria for  $\text{NO}_3^- + \text{NO}_2^-$ . Concentrations of  $\text{NO}_3^- + \text{NO}_2^-$  in Waikolu Stream, however, were consistent with many other streams in the Hawaiian Islands (Figure 16).

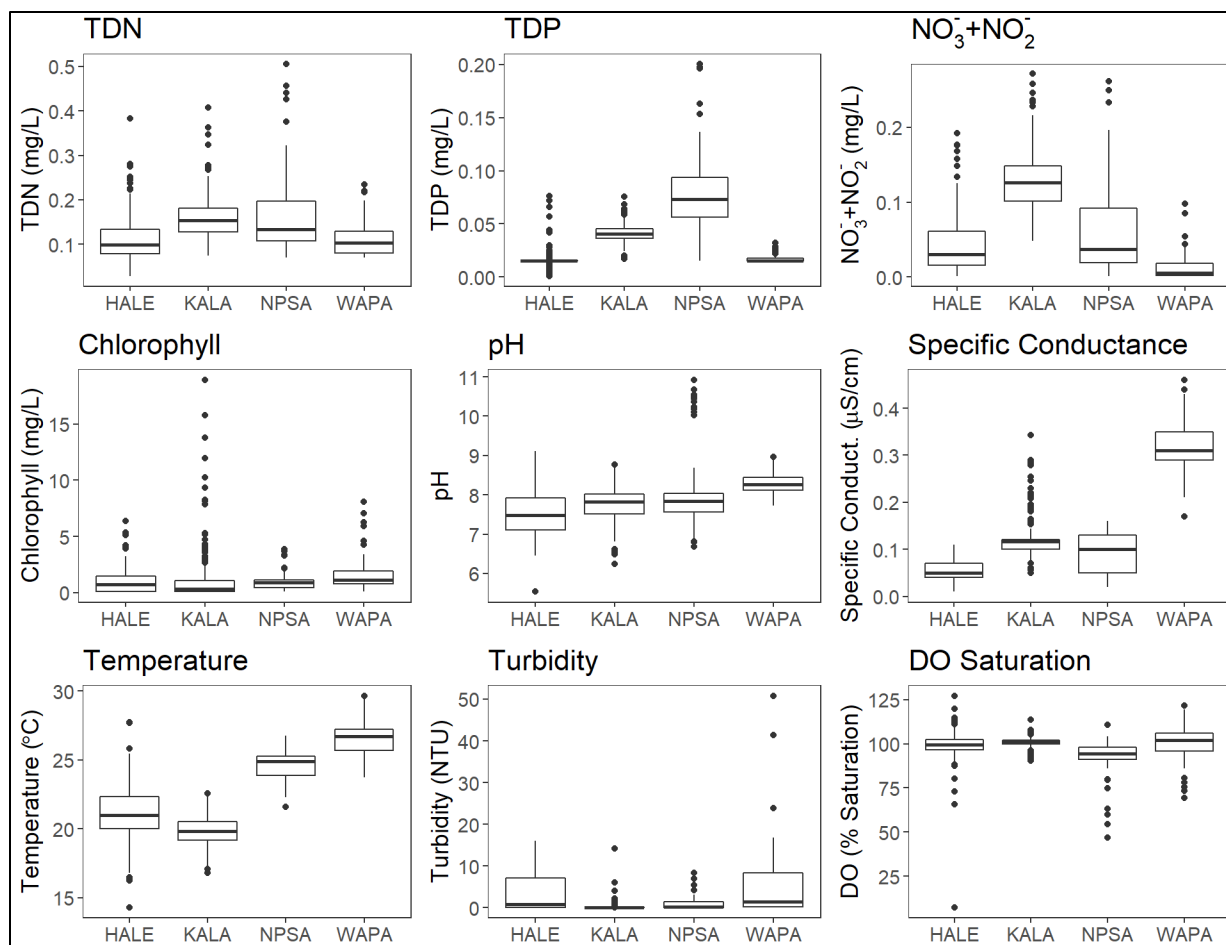


**Figure 15.** Comparison of water parameters in Waikolu stream with those in streams of other Pacific island national parks. HALE: Haleakala National Park 2007–2017, KALA: 2007–2017 (present study), NPSA: National Park of American Samoa (2009–2011), WAPA: War in the Pacific National Historical Park (2007–2012).

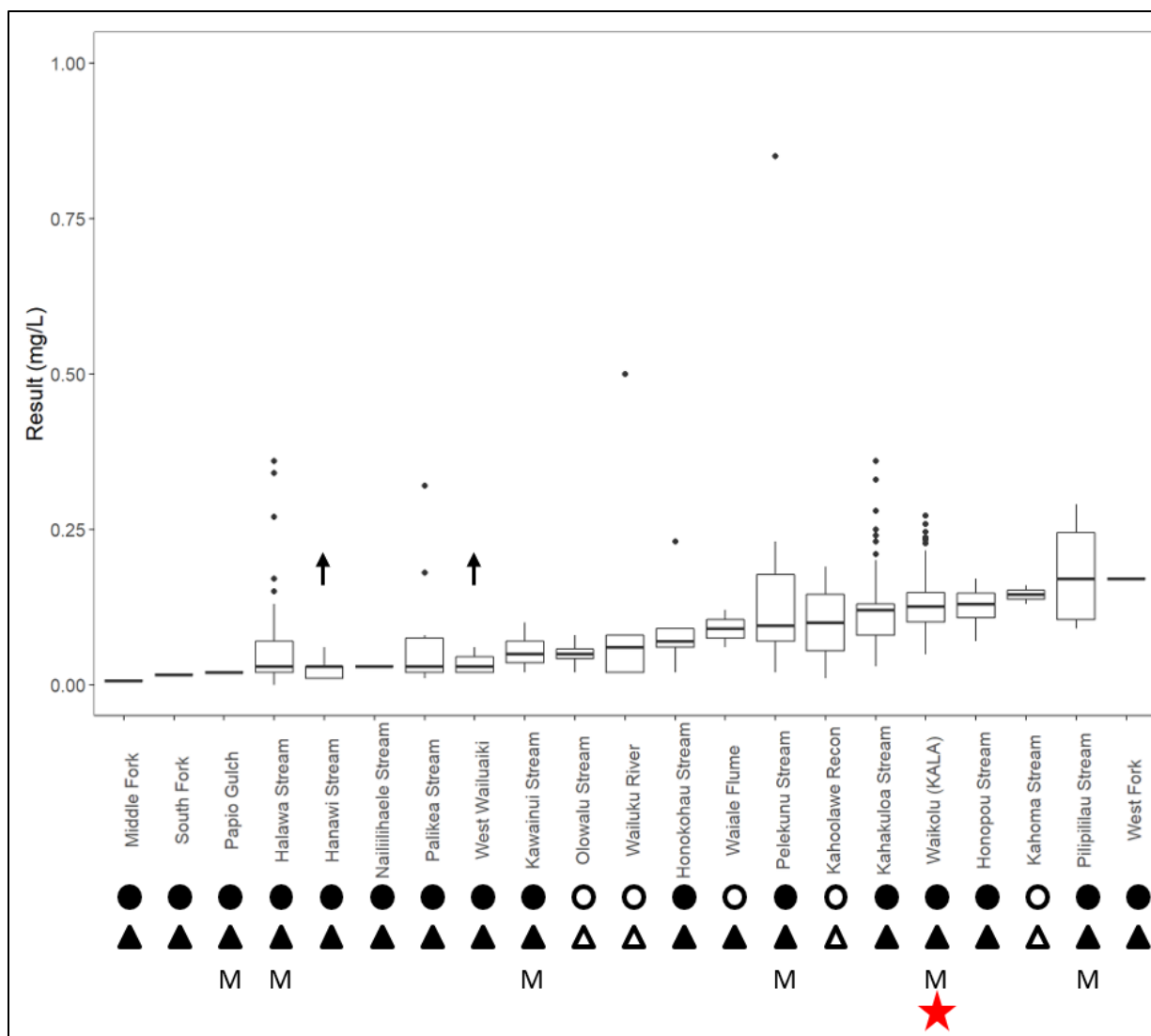


**Figure 16.**  $\text{NO}_3^- + \text{NO}_2^-$  concentrations found in Hawaiian streams. Closed circles: forested, Open circles: Partially or not forested, Closed triangles: windward side, Open triangles: leeward side, M = Moloka'i, Arrows: high outlier (Hanawi: 2.0 mg/L, West Wailuaiki: 3.9 mg/L). Star: data from present study. All other data: USGS Hawaii Water Science Center.

Raikow and Farahi (2014a) reported that Waikolu Stream exceeded state standards for  $\text{NO}_3^- + \text{NO}_2^-$  based on data from 2007–2011, which is included in the dataset used here. Geometric means of  $\text{NO}_3^- + \text{NO}_2^-$  concentration over the study period were consistently higher than state water quality standards (Table 7). Total nitrogen measured in 2014 and 2015 did not exceed state standards. Note that while  $\text{NO}_3^- + \text{NO}_2^-$  is a portion of TN, there are different standards for each, thus  $\text{NO}_3^- + \text{NO}_2^-$  standards can be exceeded while TN standards are not. Total phosphorus standards were exceeded in the dry seasons of 2014 and 2015, but not the wet season of 2015. Turbidity never exceeded standards, but sampling was limited to base flow conditions which are normally clear due to low flows not stirring sediment or transporting sediment newly displaced in the watershed.

Direct comparison of water quality parameters between water bodies measured at different times by different agencies must be parsed carefully. Public databases contain much water quality data on Hawaiian streams, but methodological details vary widely including the number of samples taken, the time frame of sampling, and equipment used. Moreover, such comparisons are opportunistic and thus limited in scope. In addition, nutrient species may not be directly comparable, or only partially comparable. For example, relatively extensive nitrate ( $\text{NO}_3^-$ ) data is available for 17 Hawaiian streams in public databases, with values ranging from detection limits (very low or near zero concentrations) to over 1.0 mg/L. Other public data is separately classified as  $\text{NO}_3^- + \text{NO}_2^-$ , thus directly comparable to the present study, given stated general caveats.

Comparing  $\text{NO}_3^- + \text{NO}_2^-$  measured in Waikolu Stream to  $\text{NO}_3^- + \text{NO}_2^-$  measured in assorted streams in the Hawaiian Islands, Waikolu Stream was not exceptional (Figure 16). The lowest concentrations of  $\text{NO}_3^- + \text{NO}_2^-$  were found in forested streams on the windward sides of Maui and Moloka‘i. Streams draining partially forested watersheds, partially developed watersheds, or on the leeward side of islands had higher concentrations, but there were also streams with forested watersheds on windward island sides with higher concentrations, including Waikolu Stream and other forested windward streams on the Island of Moloka‘i. Hence Waikolu Stream does not stand out as an exception among Hawaiian streams with regard to  $\text{NO}_3^- + \text{NO}_2^-$  in terms of position on the island or watershed land cover. These patterns are consistent with watershed characteristics being weak predictors of water quality in streams of the Island of Hawai‘i (Michaud and Wiegner 2011).

Lewis et al. (1999) showed that nitrate yield ( $\text{mass} \cdot \text{area}^{-1} \cdot \text{time}^{-1}$ ) in “minimally” disturbed tropical watersheds increased with runoff ( $\text{mm of water} \cdot \text{yr}^{-1}$ ) logarithmically. This meant an initially rapid increase in nitrate being flushed from watersheds followed by a slower increase at high runoffs. Accounting for elevation change in the watershed improved the statical quality of the relationship. The authors suggested a refinement to the widely cited Meybeck (1982) worldwide river nutrient concentration average estimate of tropical nitrate concentrations from 0.075 mg/L to 0.120 mg/L. This work has direct relevance to Waikolu Stream, and all Hawaiian streams, by: 1) demonstrating that watersheds with high runoff, i.e., as a function of high precipitation, yield more nitrate, 2) high elevation changes, i.e., as found in deeply cut valleys, yield more nitrate, and 3) tropical stream systems may naturally yield more nitrate than previously recognized. In Hawaii, older soils have more nitrate than younger soils due to accumulation of atmospheric deposition and in-situ nitrogen fixation (Vitousek 2004) and nitrogen loss from soils increases with slope (Vitousek et al. 2003).

Moloka'i is up to two million years old, and older than both Maui, where HALE is located, and the Island of Hawai'i, which could also contribute to differences between observations made in the present study and those made by Michaud and Wiegner (2011).

A reasonable question to consider is whether the study design affected the distribution of observations, e.g., by missing times when  $\text{NO}_3^- + \text{NO}_2^-$  concentrations might have been different such as during high-flow events which were explicitly avoided for safety. High flow conditions, floods or spates, in Hawaiian streams have exceptionally rapid onsets compared to North American drainage networks and can build to a 60-fold increase in discharge in a little as 15 minutes (Tomlinson and De Carlo 2003). Hawaiian stream spates are highly turbid because they carry sediments, and thus may intuitively appear to deliver higher nutrient loads to the stream and outflow to marine nearshore environments, where "load" is the total mass of material carried by a stream over a period of time and can be specified for nutrient species. Studies comparing baseflow and spate conditions demonstrate that baseflow conditions are at least as important as spates to nutrient flux in Hawaiian streams and can deliver a higher annual load to marine environments than spate conditions, counterintuitively (Larned and Santos 2000, Laws and Ferentinos 2003).

Contrasting physical mechanisms, however, may make such a relationship between discharge and nutrient flux complex. For example, while much less water is flowing through a stream during baseflow conditions, the stream experiences baseflow for a much longer time over the course of a year than it experiences spates (e.g., Figure 2). High rainfall may flush stored material out of the watershed, but high flow moves that material out of the drainage network quickly. Larned and Santos (2000) observed increases in the concentrations of  $\text{PO}_4$ ,  $\text{NO}_3^- + \text{NO}_2^-$ ,  $\text{NH}_4$ , and silicon (Si) during some spates as compared to baseflow in three Oahu streams within protected forests, but the ranges of concentrations overlapped between baseflow and spates. In a radically altered Hawaiian stream draining a developed watershed under heavy agricultural and animal husbandry use  $\text{NO}_3^-$  concentrations and loads were higher under baseflow than spates resulting in baseflow accounting for 96% of N flux (Laws and Ferentinos 2003). These patterns suggest that nutrient concentrations in Hawaiian streams may be saturated at baseflow relative to the supply of nutrients in the watershed. In other words, high flow conditions, while delivering sediment, do not necessarily inundate Hawaiian streams with a pulse of nutrients. Further, nutrient concentrations at baseflow conditions may be at equilibrium with nutrient supplies in the watershed. Thus, current observations of  $\text{NO}_3^- + \text{NO}_2^-$  in Waikolu Stream elevated relative to some other Hawaiian streams, and exceeding state standards, are reliable. While older soils, steep slopes, and high precipitation may be contributing to  $\text{NO}_3^- + \text{NO}_2^-$  levels in Waikolu Stream, there may also be other sources. Important anthropogenic sources of nitrogen to aquatic ecosystems include fertilizer, livestock waste, and sewage but none of these sources are present in Waikolu Valley.

Diversion of water drained from the upper portion of the watershed could in theory affect nutrient concentrations in lower reaches of the stream. If contribution of nutrients to the stream is not uniform across the area of the watershed, diversion could alter overall nutrient loading by removing water that differs in nutrient load. Here, nutrient concentrations measured in upper reaches were frequently

higher than those measured downstream (Figure 11). However, less water is present in the channel at higher elevations and thus there is less water available to dilute nutrients.

Invasive species could contribute to elevated N in Waikolu stream. *Falcataria moluccana*, also known as albizia, is a non-native N-fixing tree now present in many low-elevation areas of Hawaii. Atwood et al. (2010) demonstrated that aquatic food webs in streams with albizia-invaded riparian zones can be altered by the presence of albizia leaf litter. Wiegner et al. (2013) documented dramatic increases in  $\text{NO}_3^- + \text{NO}_2^-$  concentrations in stream water below riparian stands of albizia on the Island of Hawai'i. Albizia did not alter TDP below riparian stands. MacKenzie et al. (2013) showed that breakdown of albizia leaf litter in streams occurred more rapidly than some native species, suggesting that higher rates of N release can occur during early stages of litter breakdown. The presence of *F. moluccana* in Waikolu Valley however, has not been documented. The initial vegetation inventory conducted by PACN and which included Waikolu Valley did not document *F. moluccana* (Green et al. 2014). A State of the Park report also did not mention *F. moluccana* (NPS 2015). Waikolu Valley, however, is not included in the current study design of the PACN vegetation monitoring protocol (Ainsworth et al. 2011). Poeciliid fish (including guppy, mollies, and swordtails) have been shown to increase  $\text{NO}_3^- + \text{NO}_2^-$  yield up to eight times in invaded streams on the Island of Hawai'i (Holitzki et al. 2013). These invasive fish have not been detected in Waikolu Stream during PACN surveys.

Ungulates, including pigs (*Sus scrofa*), goats (*Capra aegagrus*), and axis deer (*Axis axis*) are present in the park (NPS 2000). Disruption of understory vegetation by terrestrial herbivores is known to lead to increased soil erosion and silt loading to streams (Laws and Ferentinos 2003, Bolds et al. 2021). Ungulate droppings can increase N loading to streams (MacSween et al. 2019). Specific impacts of ungulates observed in Waikolu Valley by park personnel have included areas denuded of vegetation and subsequent erosion resulting in silt loading to Waikolu Stream. Impacts to both natural and cultural resources have made control of these invasive species a high priority (Paul Hosten, pers. comm). The further potential for ungulate droppings to contribute to N loading in Waikolu Stream increases the need for animal control in the valley.

### Temporal Patterns and Trends

Several temporal trends were detected during the study period (Figure 6). Due to the relatively small absolute magnitude of change, however, it is unclear if stochastic variation in normal multi-year ranges caused observed patterns. For example, the trend of increasing phosphorus was driven by a single low even at the start of monitoring and two high events at the end of the 10-year period. Moreover, some trends, such as increasing chlorophyll, appear to have been driven by an increase in the occurrence of outlier observations (Figure 7). Hence an increase in variability or stochastic variation, rather than an increase in the bulk of observations within a sampling event appeared to drive the trend. All detected trends occurred over very small and biologically insignificant absolute values, and as such do not warrant management concern at this time.

Unsurprisingly, seasonality was detected in several parameters. Seasonality in nitrogen may be explained by mobilization from soils by increased rain. Alternatively, periphyton (algae growing on surfaces such as rocks) might increase in biomass during dry seasons due to increased light under

sunnier skies and increased time to grow without scouring flood events thus increasing demand for suspended nitrogen. While increased mobilization of phosphorus during the rainy season might also be expected, the lack a seasonal pattern in phosphorus may be the result of an increased demand for the nutrient by in-stream periphyton, which may be extracting phosphorus from the water column at a constant maximal rate, thus keeping up with potentially increased supply during the rainy season. ENSO patterns did not clearly drive temporal patterns observed in water quality parameters.

### **Spatial Patterns**

The spatial and temporal extent of sampling over the course of the study period was intensive for a single stream relative to many streams studied for basic research purposes. As a result, subtle spatial variation was detected in many water quality parameters. For example, higher relative concentrations of  $\text{NO}_3^- + \text{NO}_2^-$  concentrations was consistently detected at 2000–3000m upstream of the mouth (Figure 11). The observed decrease in  $\text{NO}_3^- + \text{NO}_2^-$  concentrations downstream from 3000m from the mouth reflected biological uptake, e.g., by periphyton. Specific conductance was extremely low compared to streams on the island of Hawai‘i (Michaud and Wiegner 2011) and increased downstream, which may have reflected marine aerosolized salt deposited by winds (Meira et al. 2006) in lower reaches, and/or minerals mobilized from riparian soils in upper reaches.

Spatial patterns may reflect three general zones present along the main channel that produce subtle differences in water quality parameters. While the sampling frame for Waikolu Stream was the main channel, safety and practicality limited how far upstream crews could sample. Sites very high in the watershed, designated “upper reach sites,” could not be accessed for each sampling trip and sampling efforts typically stopped near the pumphouse, or site FKAL04. Sampling in upper reach sites was sufficient, however, to demonstrate that water quality parameters were generally more variable in these headwater areas. Greater variability in the upper watershed may have reflected subtle differences in areas being drained or differences in the relative contribution to discharge contributed by these areas at different times. Lower reaches consolidate water drained upstream and dilute subtle differences between water contributed by different headwater areas. Upper reaches that are 3000m from the mouth had lower temperatures and higher nutrient concentrations. The reach from 2000–3000m upstream of the mouth display transitions to slightly higher pH, higher oxygen saturations, and lower nutrient concentrations. The reach from 200m upstream of the mouth to the mouth was relatively stable spatially. While interesting, the change in absolute values over the course of the stream are small enough to not warrant management concern, besides the recommendation to examine the riparian zone for invasive N-fixing trees and address ungulates.

### **Evaluation of Sampling Regime**

The monitoring regime for Waikolu Stream appeared excessive for the size of the stream and watershed compared to sampling regimes in other PACN and IMD-monitored streams. The split panel design did not capture variation or unique conditions when comparing temporary sites to fixed sites. Moreover, the application of split panel was applied evenly to all PACN parks with streams, distributing four fixed sites and four temporary sites among all streams within a park (Jones et al. 2011). Thus, eight sites were distributed in other parks regardless of the number of streams present, stream-length, or watershed-size. For example, eight sites were assigned to HALE and split between

two streams including one tributary. Eight sites were distributed across three streams in Tutuila, NPSA. This method resulted in all KALA's eight assigned sites being placed in one stream. The most downstream fixed site in Waikolu, FKALA01, FKALA02, and FKALA03 all displayed high correlation with data obtained from the rest of the stream. One downstream site, FKALA03, reflected data collected at all other sites very well, with correlations ranging from  $R = 0.80$  to  $0.93$ , with high statistical significance for all water quality parameters (Table 8).

Streams have a physical characteristic unique among aquatic ecosystems in their linear flow (Stevens and Olsen 2004). Water in spatially broad drainage networks is amalgamated as tributaries converge and this water is mixed and delivered to stream mouths. As such, a drainage network can be monitored as whole by sampling a single downstream site. The challenge for most water quality monitoring programs is where to place a limited number of sample sites in a dendric drainage network made up of nested watersheds. But importantly, most statistical evaluations of alternative lotic water quality sample site placement regimes evaluate river networks on the order of thousands of kilometers long (e.g., Stevens and Olsen 2004, Park et al. 2006, Dobbie and Henderson 2008), or entire states (e.g., Bunn et al. 2002, Larsen et al. 2008). These sampling designs place individual sample sites on tributaries to large rivers that integrate nested watersheds that, while smaller than the whole for the river, are themselves literally thousands of square kilometers in size. Other approaches to lotic sample site placement consider where the site may be within local geomorphic contexts with the larger drainage network, because hydrologic processes change dramatically with increasing discharge as streams converge to become large rivers (e.g., Montgomery and MacDonald 2002). Such designs account for considerations that could warrant additional monitoring sites such as the presence of a potential point source of contamination, differences in land use or land cover within sub-watersheds, and sheer size. While all of these statistical evaluations of alternative sample regimes are perfectly valid and scientifically important, none of them are relevant here.

Waikolu Stream is very small, undeveloped, well protected, and with no point-sources of contamination. There are no major land cover differences between the areas drained by tributaries. The longitudinal patterns detected are minute, only detectable due to the high intensity of sampling, and do not rise to a level requiring scrutiny under long-term monitoring. Therefore, we recommend that monitoring of water quality in Waikolu Stream should be reduced. Site FKALA03 displays water quality that reflects the entire stream, as indicated by high correlation with whole-stream data. The site is in the lower reach of the stream and easily accessible. Not being located near the mouth there is no possibility of direct influence of seawater that might occur during or immediately after high tides or storm wave action. Thus, it is possible that this site alone could serve as the water quality monitoring station for Waikolu Stream, if power analysis can demonstrate that one site is sufficient to detect selected levels of change. We further recommend considering adding nutrient analytes to better characterize biogeochemical cycling in this stream, including TP, TN,  $\text{NH}_4^+$ , and  $\text{PO}_4$ . Reduction from eight sites to one site will result in large cost savings for the PACN water quality monitoring program without compromising the quality of the dataset.

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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 491/193219, April 2024

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1201 Oakridge Drive, Suite 150  
Fort Collins, CO 80525