Strategic Monitoring and Resilience Training in the Ala Wai Watershed, O‘ahu: Seasonal and Episodic Variability

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By
Solomon T Chen

Thesis Advisor

Dr. Brian Glazer

I certify that I have read this thesis and that, in my opinion, it is satisfactory in scope and quality as a thesis for the degree of Bachelor of Science in Global Environmental Science.

THESIS ADVISOR

Brian Glazer

Dr. Brian Glazer
Department of Oceanography

For my mom Amy and my brothers Mathew and Feynman, we are who we are today because we have each other.

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ABSTRACT

The Ala Wai Canal is an artificial estuary connecting three major streams (Makiki, Palolo, Mānoa) and numerous city drainages to the ocean in Honolulu, Hawai'i. The Ala Wai Canal is where the terrestrial influence from the watershed meets oceanic forcing (e.g. tides, salinity). However, extensive urbanization has led to severe eutrophication in the Ala Wai Canal. Limited previous watershed data inhibits restoration and resilience efforts in Ala Wai Canal and the watershed. In order to understand the biogeochemical interactions and anthropogenic inputs within the watershed, this study aims to construct high-resolution spatial and temporal characterizations of current physical and chemical parameters. Monthly water quality surveys and sampling were conducted at 12 sites along three major streams in the watershed; bathymetry mapping, sensor profiling, and discrete water sampling were conducted in the canal and in the nearshore water. A high-resolution bathymetry survey in the canal was conducted at the beginning of the study period. Sensor data included temperature, salinity, dissolved oxygen, chlorophyll, and turbidity, while discrete samples were analyzed for dissolved inorganic nutrients and dissolved inorganic carbon. Vertical stratification and horizontal gradients in the Ala Wai Canal were strongly affected by runoff from episodic rain events, tidal mixing, and canal bathymetry. Bathymetry mapping and sensor surveys indicate that lateral mixing is primarily inhibited by sediment shoals, while vertical mixing was largely affected by salinity gradient. Increased runoff facilitates the vertical mixing downstream to major freshwater inputs. Data also shows that the restricted end of the canal was largely anoxic in the bottom water due to limited ventilation and enhanced organic matter respiration. Quantification of physical/chemical parameters can assist in understanding urbanization and ecological

effect, which is especially important for future planning, legislation, engineering, and resilience decisions.

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1.0 INTRODUCTION

1.1 Eutrophication in Hawai‘i

Among all anthropogenic environmental changes, eutrophication is particularly important because of its impacts on both inland and coastal waters due to their immediate proximity to human activities. Human activities have accelerated and expanded eutrophication with nutrient discharge from both point and non-point sources (e.g. urbanization, agriculture). Excessive nutrient input induces increased metabolism, altering biogeochemical processes, and fluxes.

Study and management of eutrophication are particularly important for the island community of Hawai‘i. Due to the high population density, impacts of eutrophication have a direct effect on the adjacent coastal and marine ecosystems. These ecosystems are heavily relied on by the community for its services in the recreation and tourism industry. Management of water quality in these ecosystems is of vital importance for both the economic benefits and sustainability planning. A quantitative understanding of these systems provides a robust argument for sustainable management as well as establishes a basis for future experiments. Advancing our understanding of these systems and their interconnection is the key to providing a guideline for future protection, restoration, and engineering.

1.2 Ala Wai watershed and canal

The Ala Wai Canal was constructed by the US Army Corps of Engineers from 1921 to 1928. It was designed to drain the wetland of Honolulu Waikiki ahupua‘a. Ahupua‘a, the traditional Hawai‘ian land division system, generally enclosed the area of a watershed from the mountain to the sea. The marshes along the south shore of O‘ahu were drained with this canal, providing lands for developments, which transformed about 645 acres of land into the modern-day Waikiki (Craig R Glenn & McMurtry, 1995). Waikiki, the world-renowned tourist destination, is home to numerous hotels, resorts, timeshares, stores, and local residences. Stretching along the northern boundary of Waikiki district from near the Kapahulu avenue to the Ala Wai boat harbor, the canal was constructed approximately 3 kilometers long. Water from the Ko‘olau Mountains, Mānoa and Palolo valleys ran through Makiki, Mānoa, and Palolo streams before being drained into the canal. Palolo and Mānoa streams were channeled together to connect to the canal via single drainage (fig 2.2). Makiki stream was channelized before connection to the canal as well. The canal was originally designed to have two outlets for better flushing of sediment into the ocean, but the plan was rejected due to the concern that an eastern outlet may cause coastal water contamination along Waikiki beach. Since the completion of construction, the canal has been dredged three times, in 1967, 1978, and 2002. The fourth dredging project was set to commence in 2019, planning to dredge the entire canal and clean up accumulated sediments as part of the improvement project (Honolulu C&C).

Concerns about floods, water quality, and potential pollution of heavy metals had been raised since the completion of the canal. Firstly, the canal was subjected to flooding due to tidal influences and shoaling of the canal from sediment accumulation; it can be especially vulnerable during storms and king tides events (Fletcher, Boyd, Neal, & Tice, 2010). Secondly, water quality has been a severe concern. Excessive nutrient input has promoted eutrophic conditions and high biological productivity in the canal, which was only matched by few other water bodies around the world (C. R. Glenn, Rajan, McMurtry,

& Benaman, 1995). As part of the hypereutrophication, anoxic conditions were reported in a previous study (Gonzalez, 1971). The canal is also reported to be a source of foul odor, which may be a result of potential hydrogen sulfide production in anoxic sediments (Laws, 1993a). In addition to the severe eutrophication, heavy metal deposition was detected in the sediments, including lead, zinc, and cadmium (De Carlo & Spencer, 1995).

1.3 Ala Wai Canal as an estuary

The Ala Wai Canal supplanted the functions of marshes and farms, becoming the estuary of Waikiki ahupuaʻa. The canal was characterized as a so-called type B estuary, where the saltwater wedge dominates the volume of the canal (Laws, 1993a). Generally, a type B estuary retains most of its sediments from run-off and is likely to have higher biological productivity than any other type of estuary (Biggs & Cronin, 1981). Despite the small size, the canal carried general characteristics of a type B estuary; because of its geometry and sediment shoaling, the canal is poorly mixed with large vertical salinity gradient dominate the vertical mixing process in the canal (Nuss, 2016). It was reported to have persisted anoxic bottom water near the dead end of the canal in the previous study (Laws, 1993a). Suggested by the previous study, the canal was also significant to modeling processes of storage and transport of sediments and various nutrients (C. R. Glenn et al., 1995). Efforts had been made to estimate the budget and net flux of particulate carbon, but the lack of benthic respiration measurements and allochthonous input could only provide a rather crude estimation (Laws, 1993a).

1.4 SMART Ala Wai project: research goal

To facilitate a quantitative understanding of the watershed, a team of University of Hawaiʻi faculty and staff initiated the SMART Ala Wai project: Strategic Monitoring And Resilience Training (SMART) in the Ala Wai watershed (smartalawai.org). The SMART Ala Wai project aimed to assemble a sampling and observation network for water quality monitoring in the Ala Wai watershed. The goal was to fill the void of up-to-date observational data. This study, as part of the SMART Ala Wai project, focused on:

1) Providing an overview of the current conditions of stream water quality in the watershed. The goal was to collect samples and produce data for spatial analysis. The spatial comparisons in water quality parameters could provide a basis for specific experiments and future assessments.
2) Providing an up-to-date comparison to previous studies by utilizing high-frequency sampling sensor technology as well as a low-cost sensor network. The physical and chemical conditions in the canal were produced with a custom sensor package, bundling sophisticated, commercially available sensors with low-cost sensors to achieve a high spatial resolution of water sampling.
3) With available data on water quality, nutrient loading, and hydrology data, this study attempted to estimate the nutrient budgets and net nutrient fluxes of the canal. The estimation of nutrient budget and fluxes may provide a comparison between the modern condition and previous studies. The estimations of nutrient fluxes may also shed a light on the origin of different nutrient species, therefore provide recommendations for future management efforts.

2.0 METHODS

2.1 Site description

The Ala Wai canal is an artificial waterway located on the south shore of island O‘ahu, extending from the Ala Wai yacht club to Kapahulu Avenue as the northern boundary of the Waikiki district of O‘ahu (fig 2.1). The Canal is approximately 3.2 km of length and various in width from 51 to 83 m with a 55° curve at about 1 km from the mouth (Fryer, 1995). The canal was originally dredged to be 4-7.5 m deep from its mouth to the bend and 3-6 m from its bend to the canal dead-end (Laws, 1993b). Currently, the water depth of the canal ranges from 0.8m to 3m due to accumulated sedimentation.

The Ala Wai Canal receives freshwater primarily from three principal watersheds: Mānoa, Palolo, and Makiki (fig 2.2). Freshwater from the Mānoa-Palolo confluence enters the Canal approximately 1.8 km from the mouth, while freshwater from Makiki Stream enters at the bend of the canal 0.8 km from the mouth. On average, the Mānoa and Palolo stream together contribute about 90% of the freshwater discharge into the canal, the Makiki stream and runoff from Ala Mānoa area contribute to the remainder. As the primary source of freshwater, runoff is one of the most significant elements that influence the mixing dynamics in the canal, which makes the rainfall an important factor in this watershed. Within the watershed, sampling and monitoring stations are established by the USGS, Commission on Water Resource Management (CWRM), and smartcoastline.org website for environmental data including rainfall and stream level (table 2.4). These existing data can be used to supplement the water budget estimation in the canal.

Figure 2.1: Aerial image of canal transection sites within Ala Wai Canal, O‘ahu, Hawai‘i.

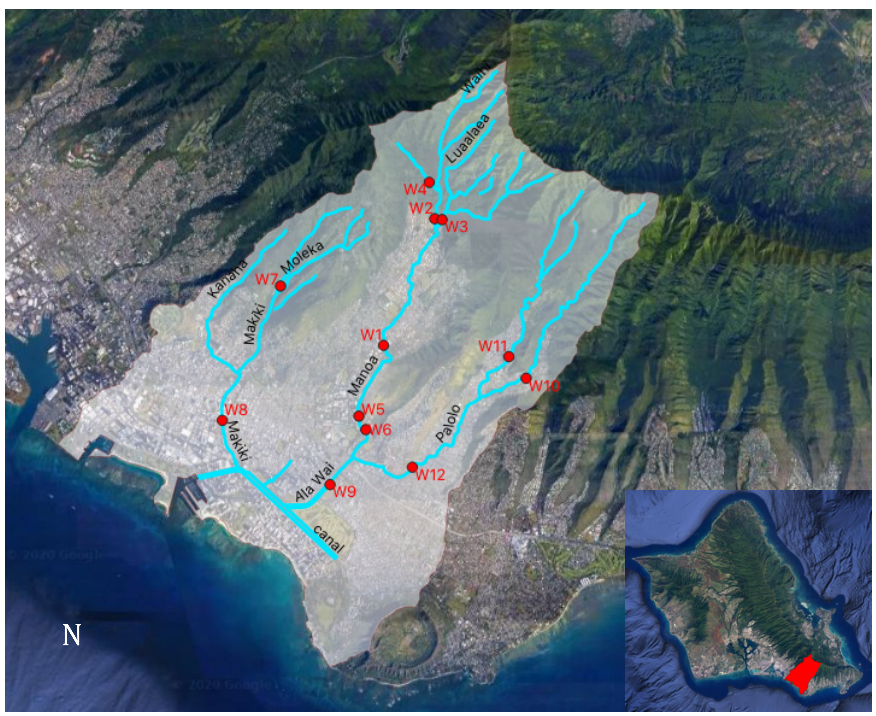

Figure 2.2: Aerial image of watershed sampling sites within Ala Wai watershed. GIS data source: Hawai‘i Statewide GIS Program (http://geoportal.Hawai‘i.gov/)

2.2 Field sampling: canal transects

Sampling along the Canal transect consisted of two major elements: discrete water sampling and water quality profiling with sensor packages. Between August 2018 and 2019, canal transects were conducted roughly on a monthly basis (Table 2.1). To standardize the sampling condition, canal transects were conducted during high tides between 8:00 AM – 2:00 PM local time. All transects started from the oceanic side of the canal (site 11), proceeding toward the dead-end. Discrete water sampling and sensor profiling were conducted at eleven stations along the canal; two stations in the Ala Wai Boat harbor, and five stations offshore (figure 2.1).

Discrete water samples were collected at eight of the sampling sites (table 2.2). At each of the discrete water sampling site, water samples were collected at the bottom, mid-depth, and surface. The surface water samples were taken from no deeper than 0.3 meters while the sampling depths for mid-depth and bottom varied. A 1L polycarbonate bottle was filled and kept at 0°C for no longer than 6 hr before subsampling and processing for analyses. The samples were then filtered, divided, and frozen for further analysis. Samples were processed for total nitrogen (TN), total phosphorus (TP), dissolved inorganic nutrients (DIN), dissolved organic carbon (DOC), and chlorophyll analysis.

In addition to the discrete water sampling, high-frequency sensor profiling was conducted at all sampling stations. The sensor package included a custom depth/pressure logger (Huliwai, smartcoastline.org), a temperature and conductivity sensor (Aanderaa 4319A, Aanderaa Data Instrument AS), an optode (Aanderaa 4330F, Aanderaa Data Instrument AS), a chlorophyll concentration and turbidity sensor (FLINTUS, Sea-Bird Scientific).

Table 2.1 Sampling date and conditions

Sample date	High tide time (HST)	Height of high tide (ft)	start time (HST)	Average air temperatue (°C)	Stream discharge rate (cfs)	Wind Speed (m/s, degree)
10/21/18	02:06	2.07	08:11	29.37	18.05	5.59, 121°
11/29/18	09:30	1.91	09:42	28.39	12.92	1.59, 192°
01/20/19	03:54	2.59	08:14	27.11	9.97	0.79, 135°
02/18/19	03:24	2.31	08:39	22.25	27.39	4.19, 71°
03/22/19	05:18	1.81	08:15	24.27	8.46	2.68, 93°
04/20/19	04:30	1.33	07:46	24.86	8.62	3.27, 103°
06/04/19	04:06	0.80	09:13	27.37	18.92	3.08, 117°
08/31/19	05:12	1.81	10:20	31.84	4.66	2.67, 113°
09/29/19	04:54	2.24	08:08	28.63	14.53	2.91, 99°

Table 2.2 Canal sampling sites and type of sampling

Site	Latitude	Longitude	Sampling type
1	21.275267	-157.81796	Sensor profile + water sampling
2	21.2759977	-157.8189	Sensor profile only
3	21.2781479	-157.82087	Sensor profile + water sampling
4	21.2799704	-157.82299	Sensor profile only
5	21.2829688	-157.82643	Sensor profile + water sampling
6	21.2846653	-157.82865	Sensor profile only
7	21.2870673	-157.83144	Sensor profile + water sampling
8	21.2886042	-157.83309	Sensor profile only
9	21.2888225	-157.83521	Sensor profile + water sampling
10	21.2884446	-157.8372	Sensor profile only
11	21.2877055	-157.84074	Sensor profile + water sampling
12	21.2864962	-157.84376	Sensor profile only
13	21.2850516	-157.84476	Sensor profile + water sampling
14	21.281861	-157.84553	Sensor profile only
15	21.282108	-157.84975	Sensor profile only
16	21.278244	-157.84998	Sensor profile only
17	21.277492	-157.84618	Sensor profile + water sampling
18	21.277258	-157.84215	Sensor profile only

2.3 Field sampling: stream sampling

Discrete water samples were also collected in the connecting watershed for estimations of biogeochemical flux. Samples collections were conducted at 12 sites along the Mānoa, Palolo, and Makiki stream (figure 2.2). The sampling sites were selected in close proximity to USGS stream gauges and existing stream level gauges for reference of environmental data, the exact coordinates of all stream sampling sites are given in table 2.4. The mean discharge rate and environmental data were accessed from USGS (https://waterdata.usgs.gov/) and the smartcoastlines.org website (table 2.3).

At each site, 500mL was collected from the streams for nutrient analysis. Sample bottles were kept at 0°C before analysis. Along with water sampling, dissolved oxygen (mg/L), water temperature (°C), conductivity (mS/cm), and salinity (PSU), and pH were measured with a Water Quality Sonde (YSI Professional Plus Multiparameter, YSI). The YSI was calibrated prior to each sampling for dissolved oxygen, salinity, and pH. During sampling, the YSI sensor probes were fully submerged in flowing streams until all readings reached stabilization.

Table 2.3: Sampling date and conditions

Date	Start time (HST)	Makiki stream discharge rate (cfs)	Mānoa-Palolo stream discharge rate (cfs)	Air temperature (°C)
08/03/2018	09:20 AM	0.02	16.17	27.26
09/15/2018	08:36 AM	0.15	34.95	28.38
10/12/2018	08:20 AM	0.08	25.19	26.90
11/24/2018	08:18 AM	0.03	14.19	25.81
12/15/2018	08:08 AM	0.03	13.37	23.86
01/26/2019	08:25 AM	0.02	12.69	20.86
02/23/2019	08:21 AM	0.02	14.22	21.64
03/23/2019	08:32 AM	0.01	8.64	22.70

Table 2.4: Coordinates of stream sampling sites and existing monitoring stations

Site	Latitude	Longitude	Existing site
W1	21.308444	-157.8095	USGS 16241600
W2	21.32836	-157.80086	USGS 16238500
W3	21.32822	-157.799611	USGS 16240500
W4	21.33408	-157.80179	CWRM 3-114
W5	21.29731	-157.81368	N/A
W6	21.2951861	-157.8125122	N/A
W7	21.31777	-157.826917	CWRM 3-115
W8	21.296639	-157.83675	USGS 16238000
W9	21.286528	-157.818556	USGS 16247100
W10	21.3032612	-157.7854042	USGS 16244000
W11	21.306667	-157.788333	USGS 16247000
W12	21.289278	-157.804639	N/A

2.4 Nutrient Analysis Site

Following sample collection, samples were brought to the lab for preparation before analysis, which was conducted via an inline filtration system with a peristaltic pump and 0.2 uM polyethersulfone filters (Sterivex). In the filtration process, 50mL of each filtered sample was collected in a new polypropylene centrifuge tube for TN, TP, DIN, and chlorophyll analysis. The filtered samples were frozen and processed in a single batch at the UH Mānoa SOEST Lab for Analytical Biogeochemistry (http://www.soest.Hawai‘i.edu/S-LAB/) via in-line oxidation on a Seal AA3 Autoanalyzer to find the concentrations of nutrients and chlorophyll (uM).

2.4 Canal Bathymetry

On sampling date 10/21/2018, a canal bathymetry profile was surveyed after the discrete water sampling with a sonar (SIMRAD Go9XSE). The sonar was mounted on the bottom of the stern of the sampling boat (Boston Whaler Montauk 17). The bathymetry survey was conducted by driving the boat across the width of the canal in a zig-zag pattern to provide a detailed grid of depth data points (figure 2.3). After the survey, the bathymetry data was processed in QGIS. The final bathymetry map was generated with triangulated irregular network interpolation and smoothed with a Gaussian filter.

Figure 2.3: Aerial image of Ala Wai Canal and survey path (shown in red dots).

2.5 Estimation of water budget and nutrient fluxes

Obtaining quantitative estimations of nutrient fluxes of the system was one of the main goals of this project. Before nutrient fluxes could be calculated, the water budget needed to be established with available data to estimate the outflow of the canal. The major component of water fluxes of the canal included inflow, outflow, evaporation, and precipitation (Equation 1). The annual rate of precipitation was accessed from Rainfall Atlas of Hawai‘i (http://rainfall.geography.Hawai‘i.edu/). The rate of evaporation was estimated base on temperature and (Equation 1, 2) (Linacre, 1977). Temperature records were obtained from the Smartcoastline.org website (https://grogdata.soest.Hawai‘i.edu/). In equation 2, T represents the mean temperature. T_d is the mean dew point temperature, $T_m = T + 0.006h$, and A is the latitude. h is the elevation. With the volume of the canal, the residence time of water could also be calculated (Equation 4). The nutrient fluxes were then estimated with canal outflow (Equation 5).

(1) *Outflow + Precipitation = Inflow - Evaporation*

(2) $$E_0 = \frac{\frac{700T_m}{100-A}+15(T-T_d)}{(80-T)} \quad (mm\ day^{-1})$$

(3) *Residence Time = Canal Volume / flux*

(4) *Nutrient Transport = Outflow Volume × Nutrient Concentration*

2.6 Data visualization

Using Ocean Data View (ODV), the canal profiling data was organized to represent salinity, temperature, DO, and chlorophyll concentration. Data on nutrient concentrations and time series plots were grouped, calculated, and plotted with Python to show the variation of water quality parameters measured during the sampling period.

3.0 RESULTS

3.1 Physical conditions in canal

To evaluate how environmental conditions affect the mixing dynamic and biological activity in the canal, environmental parameters measured during canal transects were converted into contour plots along the length of the canal from station 1 to station 11 (DO, salinity, temperature, and Chlorophyll concentration) (fig 3.1 – 3.8). The parameters were grouped together based on sampling dates to demonstrate the water quality change throughout the sampling period. One exception of canal transection occurred on sampling date 2/18/2020 due to the malfunction of depth probe on the sensor package, resulting in missing depth data. In addition to missing depth data on 2/18/2019, the profiling data of the bottom water throughout the canal was missing on 9/29/2019. The sensor package was recovered prematurely during vertical profiling throughout the canal, leaving the bottom water uncovered.

Temperature (°C) in the canal varied greatly over the sampling period with a notable pattern of seasonality. The lowest canal water temperature occurred during winter and early spring while the highest temperature occurred in late summer (fig 3.9, 3.10). The overall lowest canal water temperature was found on 3/22/2019 while the overall highest canal water temperature was observed on 8/31/2019. The spatial variation of the water temperature also followed a general pattern; water temperature generally increased as measurements progress toward the dead end of the canal (fig 3.1, 3.5). In addition, the water temperature was observed to be lower near the freshwater inlet, station 5, and station 9, on sampling date 10/21/2018, 06/04/2019, and 08/31/2019 (fig 3.1, 3.6, 3.7). The highest water temperature measurement over the sampling period occurred at site 1 on sampling date 06/04/2019, the surface water was 32.1°C. The lowest water temperature measurement over the sampling period occurred at site 5, the surface water was 24.4 °C.

Salinity (PSU) showed patterns of vertical stratification in the canal, which remained fairly constant during the sampling period (fig 3.2, 3.4). The salinity of surface water was generally lower than the bottom water of the canal. A well-stratified salinity gradient from freshwater dominant surface to ocean water dominant bottom was observed in contour plots from both 11/29/2018 and 03/22/2020 (fig 3.2, 3.4). Contrarily, the less pronounced freshwater layer was observed on 10/21/2018, 4/20/2019, 6/4/2019, and 9/29/2019; on these sampling dates, the water column salinity ranged from 5PSU to approximately 30PSU or higher. The absent freshwater layer may be attributed to enhanced vertical mixing and flushing of the canal by extra mechanical energy provided by rain events and freshwater surge. Furthermore, on sampling date 6/4/2019, almost all stations have a high salinity level of 12PSU or more. The freshwater layer was entirely absent on 6/4/2019, which may be a result of both higher freshwater discharge from streams and rising tide on that date. The change in mixing dynamic was found to be driven by freshwater discharge from the stream, which enhanced flushing and mixing in the canal. As a result, enhanced mixing reduced the overall stratification of the water column.

Dissolved oxygen concentration (uM) ranged from 50uM to 300uM over the sampling period with an observable spatial distribution trend. Surface water is observed to be generally higher in DO concentration throughout the canal (fig 3.3). In addition, the bottom water near the dead end of the canal generally has lower DO concentration, especially from station 1 to station 4 (fig 3.1, 3.4, 3.5). This pocket of water with lower DO concentration is observed on most sampling dates (DO). However, on the sampling date

9/29/2019, the DO concentration showed a different spatial distribution trend; DO concentration was higher near the dead end of the canal and decreased progressively toward the mouth of the canal (fig 3.8). This phenomenon may be attributed to sampling near noon on the date, allowing photosynthetic activity to charge the canal water with oxygen.

In addition to the physical parameters of the canal, chlorophyll concentration was made to illustrate the biological activity and its spatial distribution in the canal. The distribution of chlorophyll followed a general trend of higher concentration near the dead end of the canal. The concentration was generally more diluted toward the mouth of the canal. In addition to the general trend of distribution, higher chlorophyll concentration was observed at station 2, station 3, and station 4 on most sampling dates (fig 3.2, 3.4, 3.5, 3.6, 3.7). The higher chlorophyll concentration occurs approximately from 0.5m to 2.0m below the surface, ranging from 20ug/L to 50ug/L while the rest of the canal had much lower chlorophyll concentration. The pocket of higher chlorophyll concentration was not observed on 10/21/2018, 1/20/2019, and 9/29/2019. The canal received a higher discharge from streams on these two sampling dates.

For observation of seasonal variability, time-series of vertical profiles were plotted at station 9 and station 3 to show the general seasonal trend of two respective segments of the canal. Station 3 represents the inland portion of the canal, separated from the oceanic section by sediment shoaling near station 5 (fig 3.9). In terms of seasonal variation of temperature, the lowest temperature of the canal water was observed on 4/20/2019. The lowest temperature over the entire sampling period was observed at station 10 near the canal mouth (fig 3.10). The temperature gradually rose from 24.1°C to 26.5°C as profiling continued toward the dead end of the canal. The highest temperature was observed on

8/31/2019, the canal water temper ranged from 30°C to 32°C (fig 3.10). Chlorophyll concentration did not show apparent seasonal correlations with the temperature at both station 3 and station 9. (fig 3.9, 3.10).

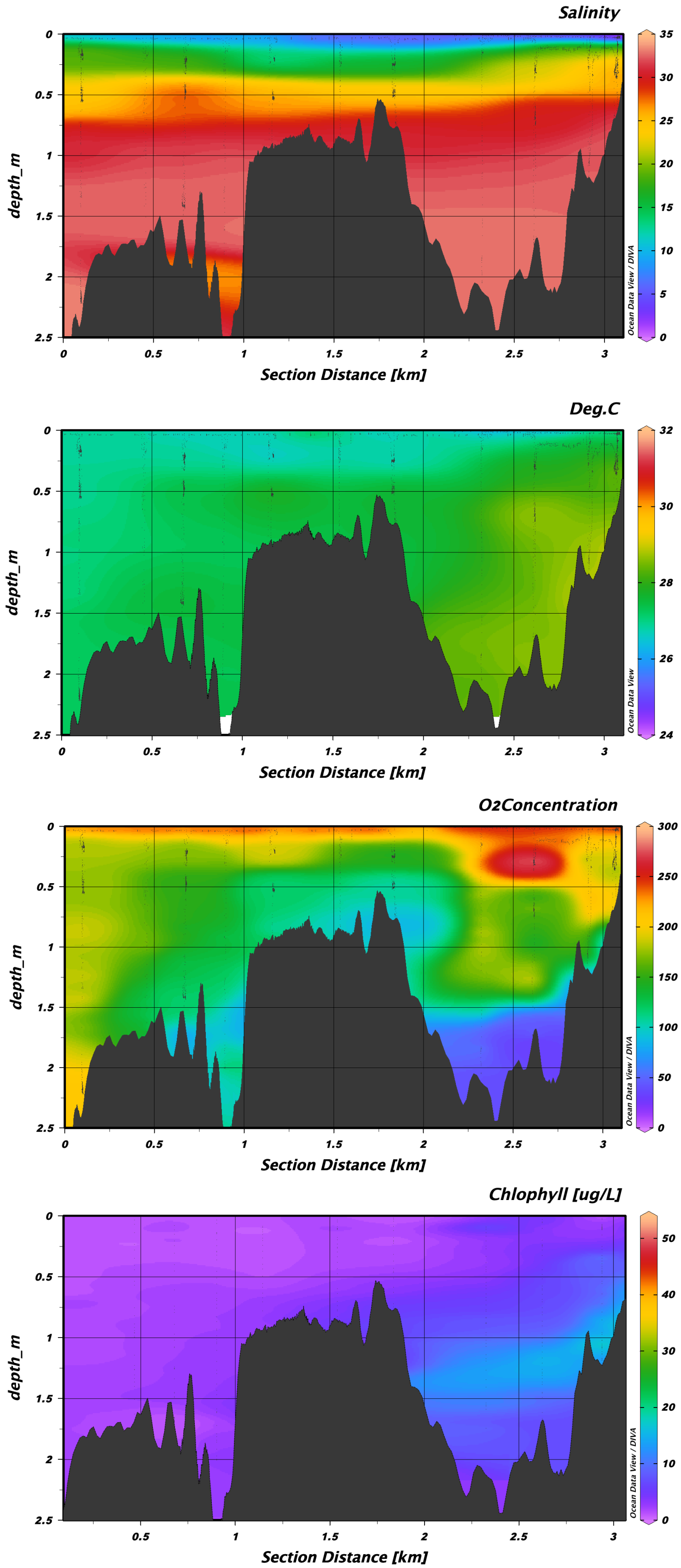

Fig. 3.1: Color shaded contour plots

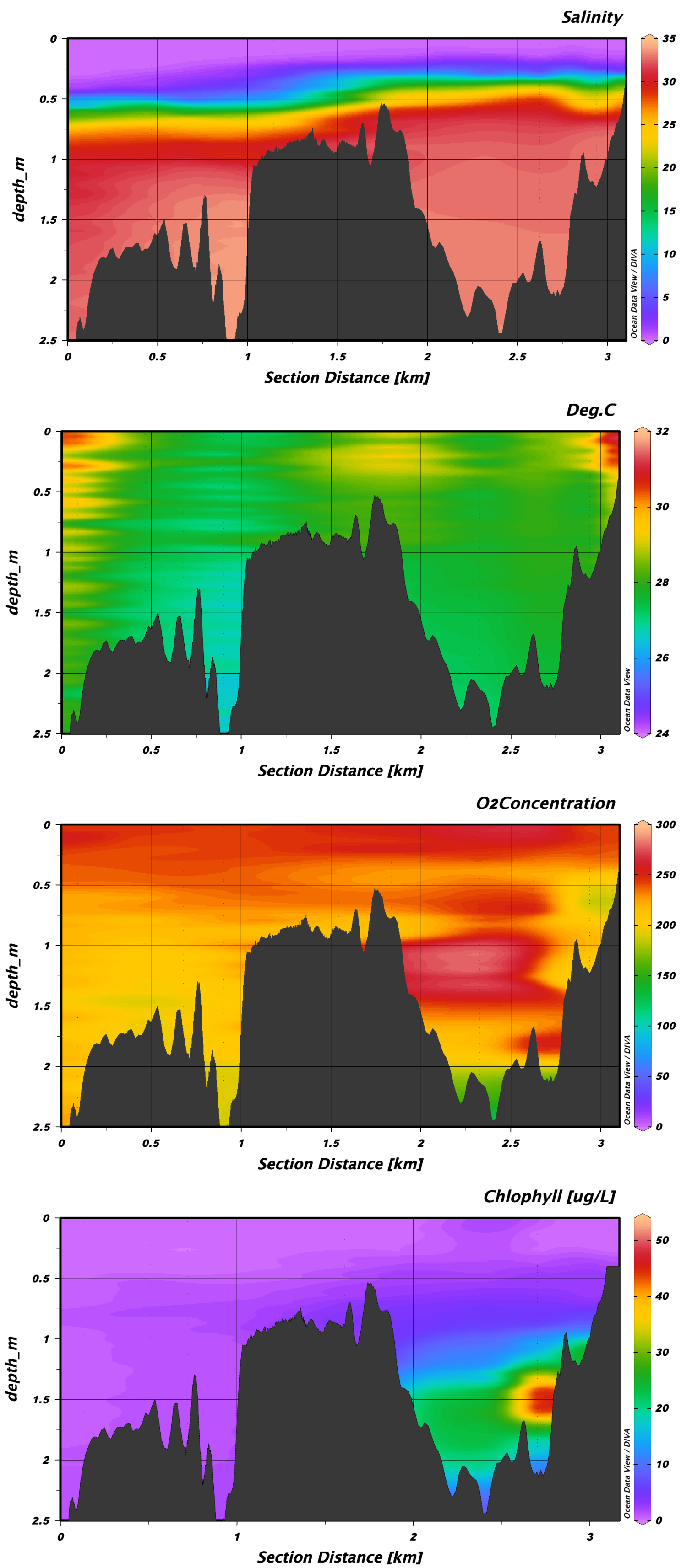

Fig. 3.2: Color shaded contour plots for canal water temperature (°C),

(mg/L), and Chlorophyll concentration (ug/L) on sampling date 11/29/2018. Section distance indicates distance from the canal

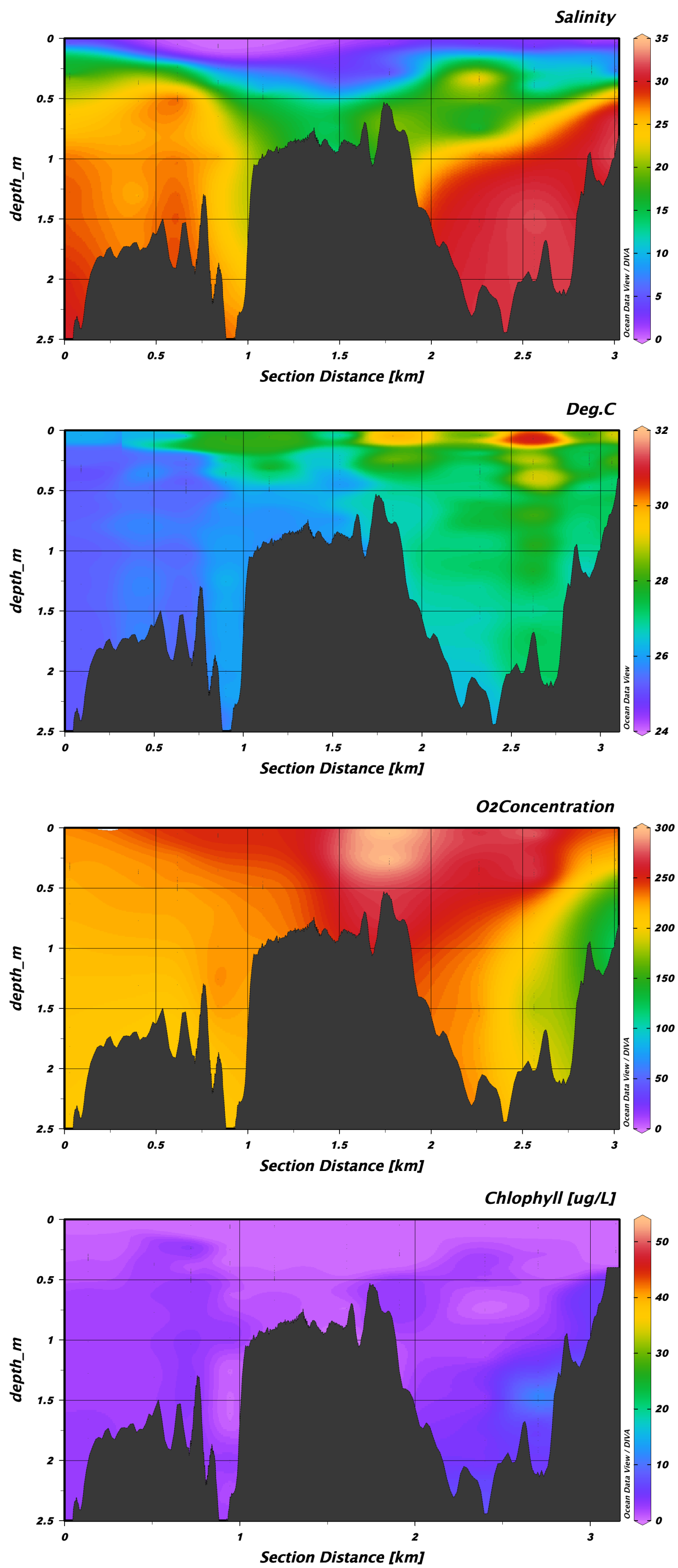

Fig. 3.3: Color shaded contour plots for canal water temperature (°C), salinity (PSU), DO concentration (mg/L), and Chlorophyll concentration (ug/L) on sampling date 1/20/2019. Section distance indicates distance from the canal mouth (harbor).

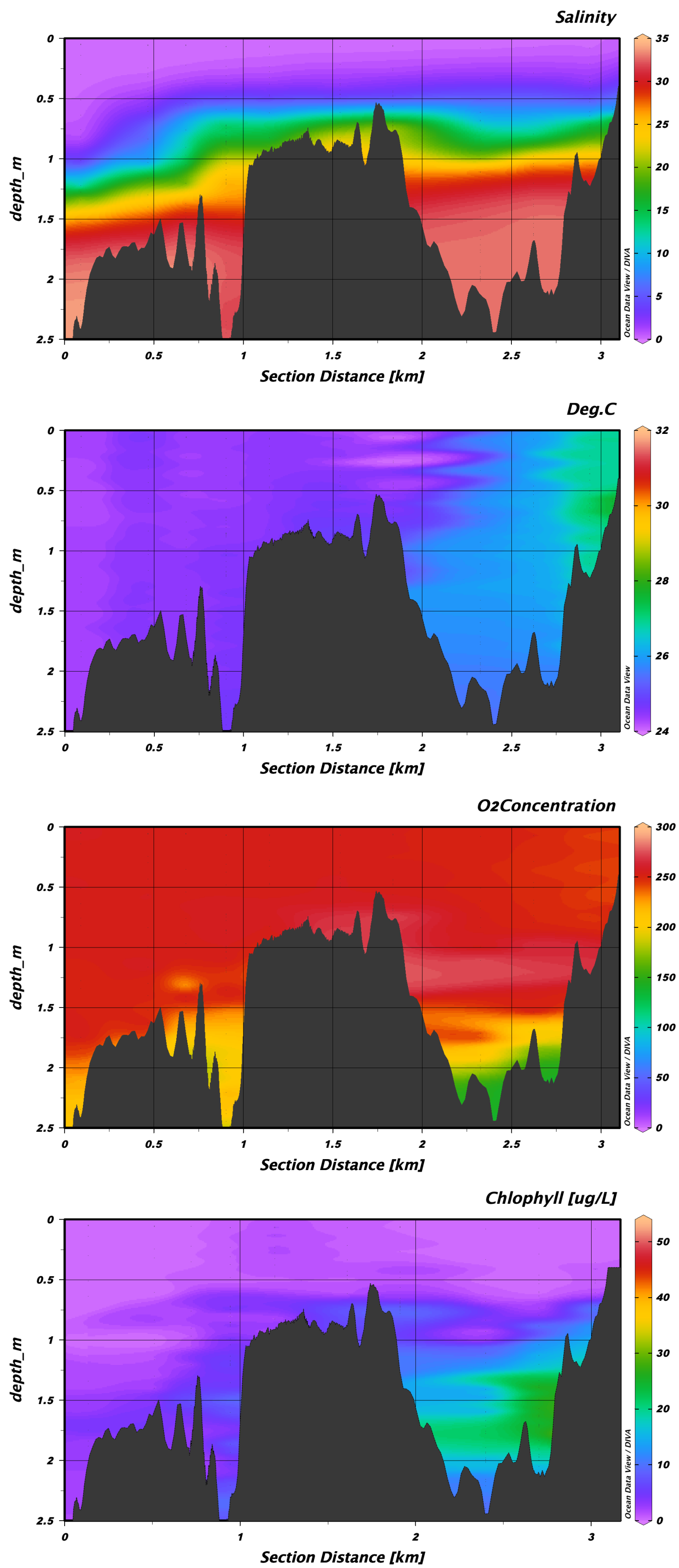

Fig. 3.4: Color shaded contour plots for canal water temperature (°C), salinity (PSU), DO concentration (mg/L), and Chlorophyll concentration (ug/L) on sampling date 3/22/2019. Section distance indicates distance from the canal

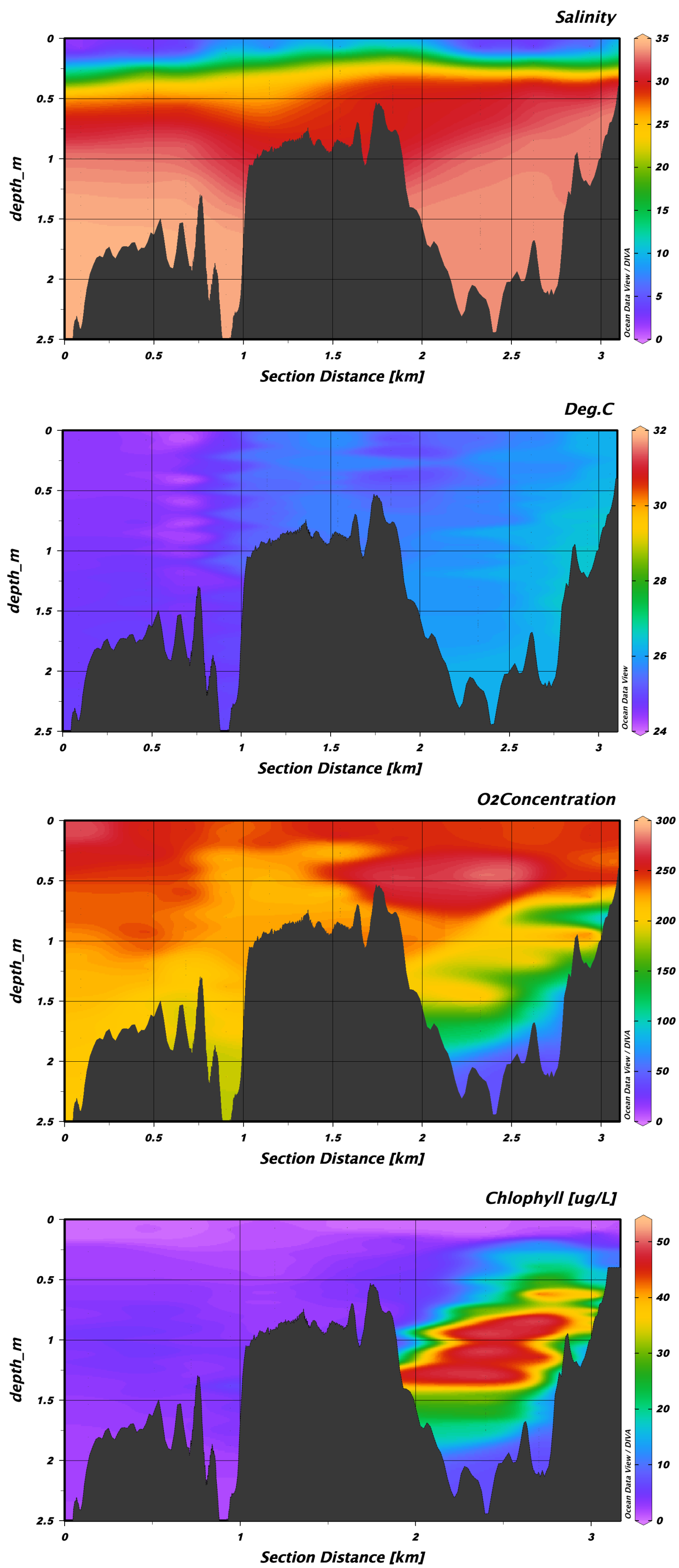

Fig. 3.5: Color shaded contour plots for canal water temperature (°C), salinity (PSU), DO concentration (mg/L), and Chlorophyll concentration (ug/L) on sampling date 4/20/2019. Section distance indicates distance from the canal

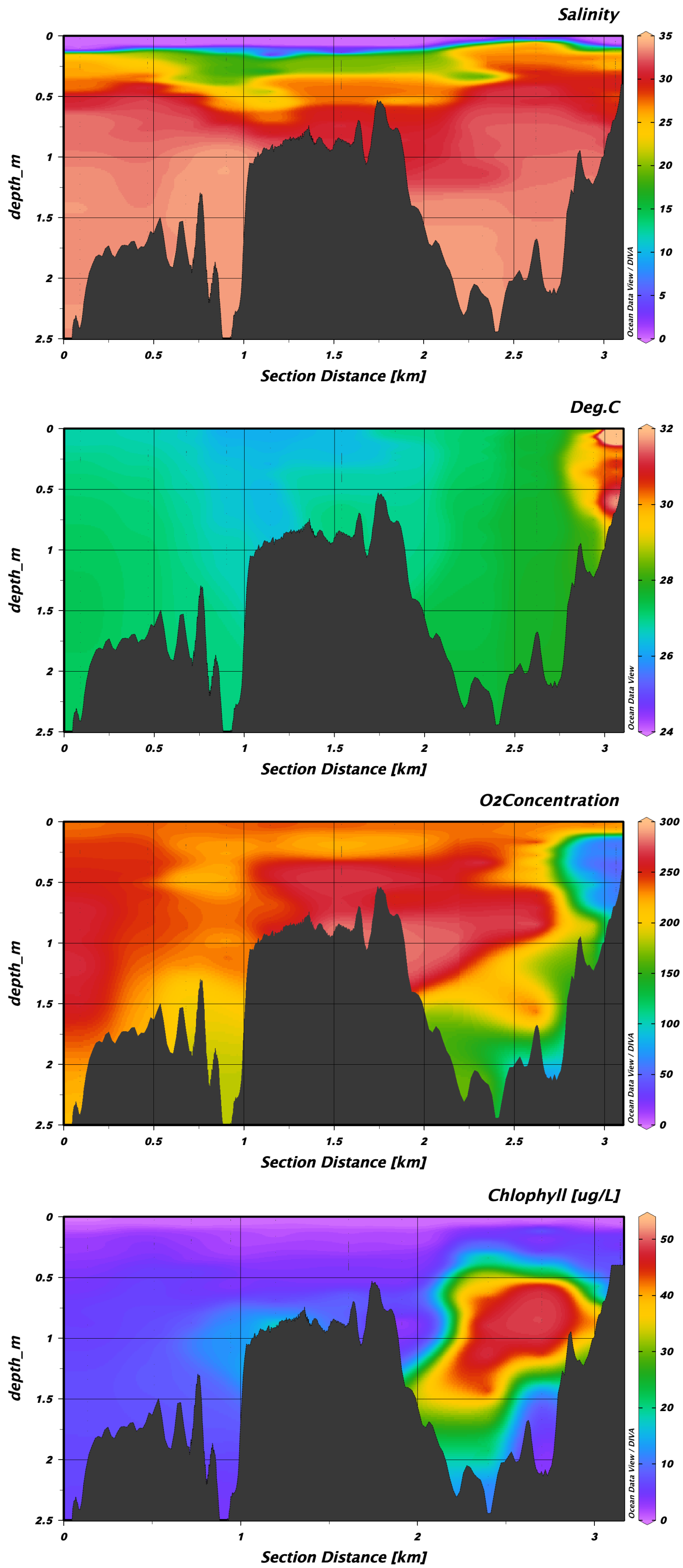

Fig. 3.6: Color shaded contour plots for canal water temperature (°C), salinity (PSU), DO concentration (mg/L), and Chlorophyll concentration (ug/L) on sampling date 6/4/2019. Section distance indicates distance from the canal

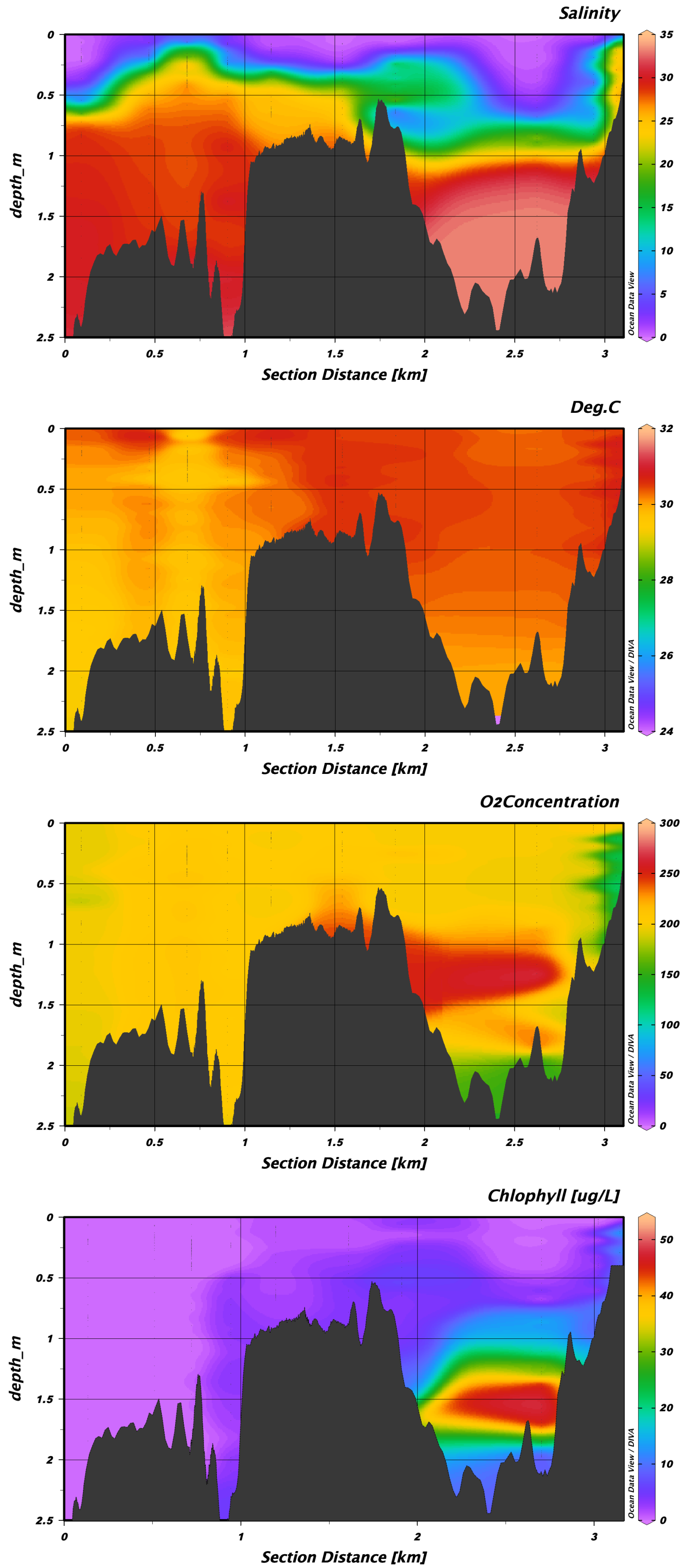

Fig. 3.7: Color shaded contour plots for canal water temperature (°C), salinity (PSU), DO concentration (mg/L), and Chlorophyll concentration (ug/L) on sampling date 8/31/2019. Section distance indicates distance from the canal mouth (harbor).

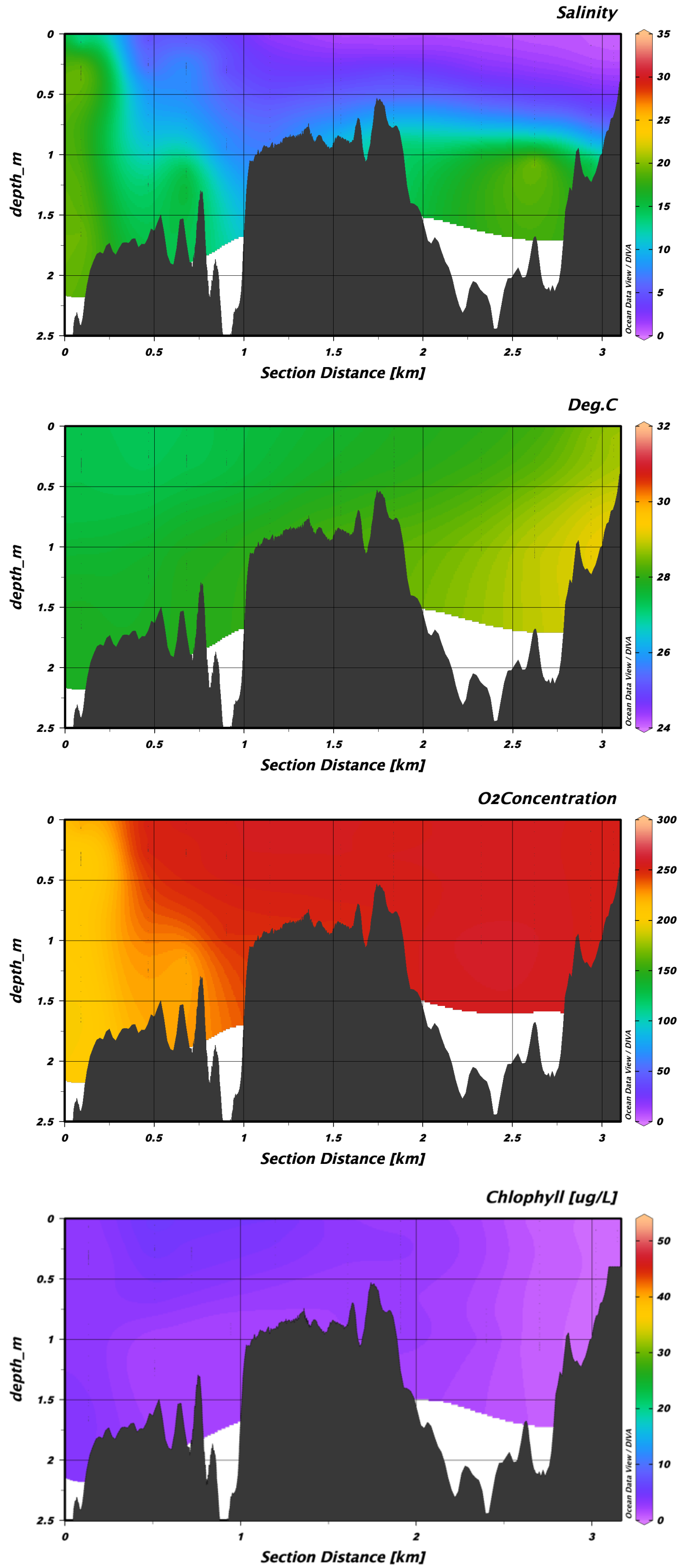

Fig. 3.8: Color shaded contour plots for canal water temperature (°C), salinity (PSU), DO concentration (mg/L), and Chlorophyll concentration (ug/L) on sampling date 9/29/2019. Section distance indicates distance from the canal mouth (harbor).

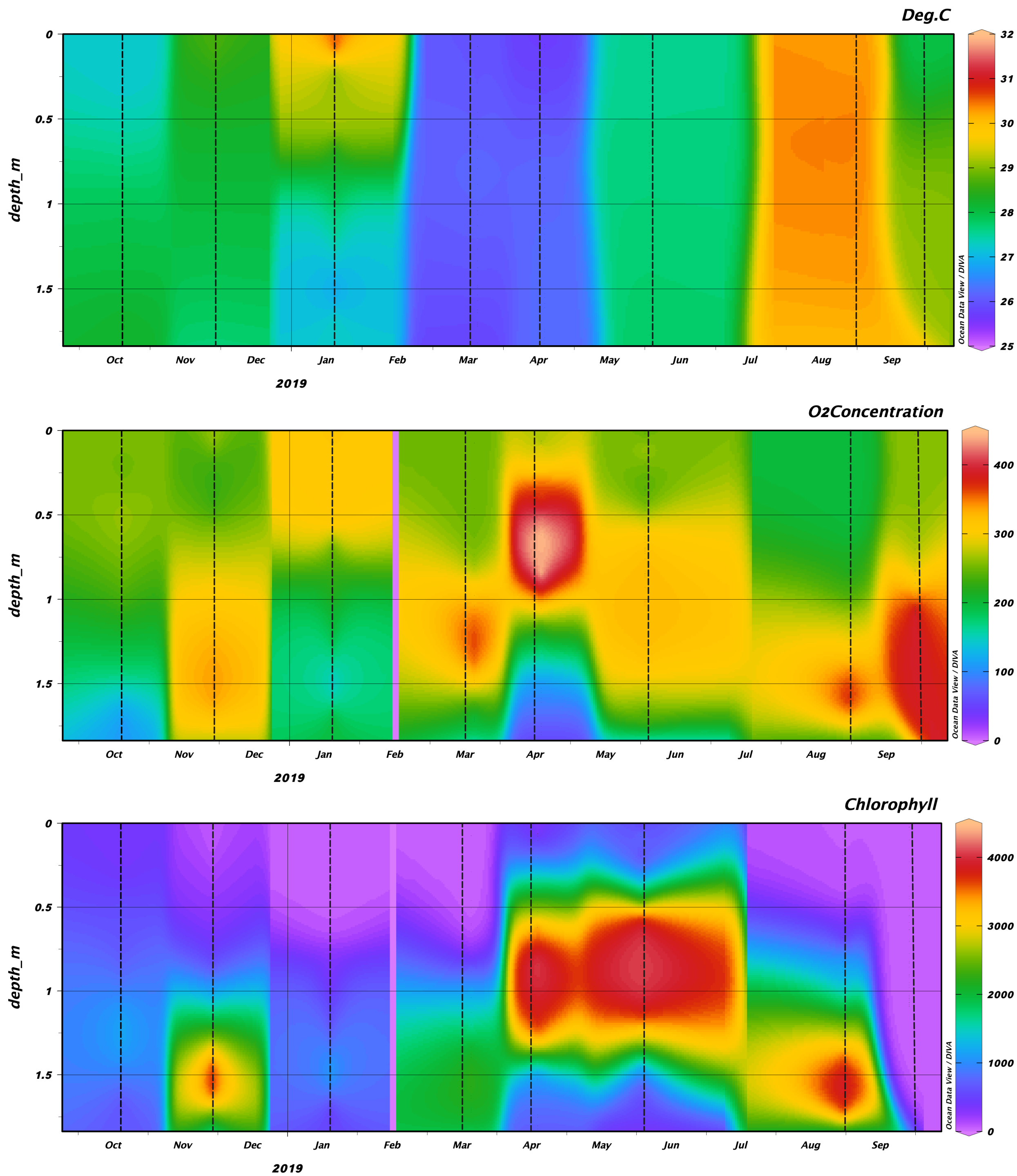

Fig. 3.9: Time-series plot at station 3, near the canal dead end. Dash lines mark sampling dates.

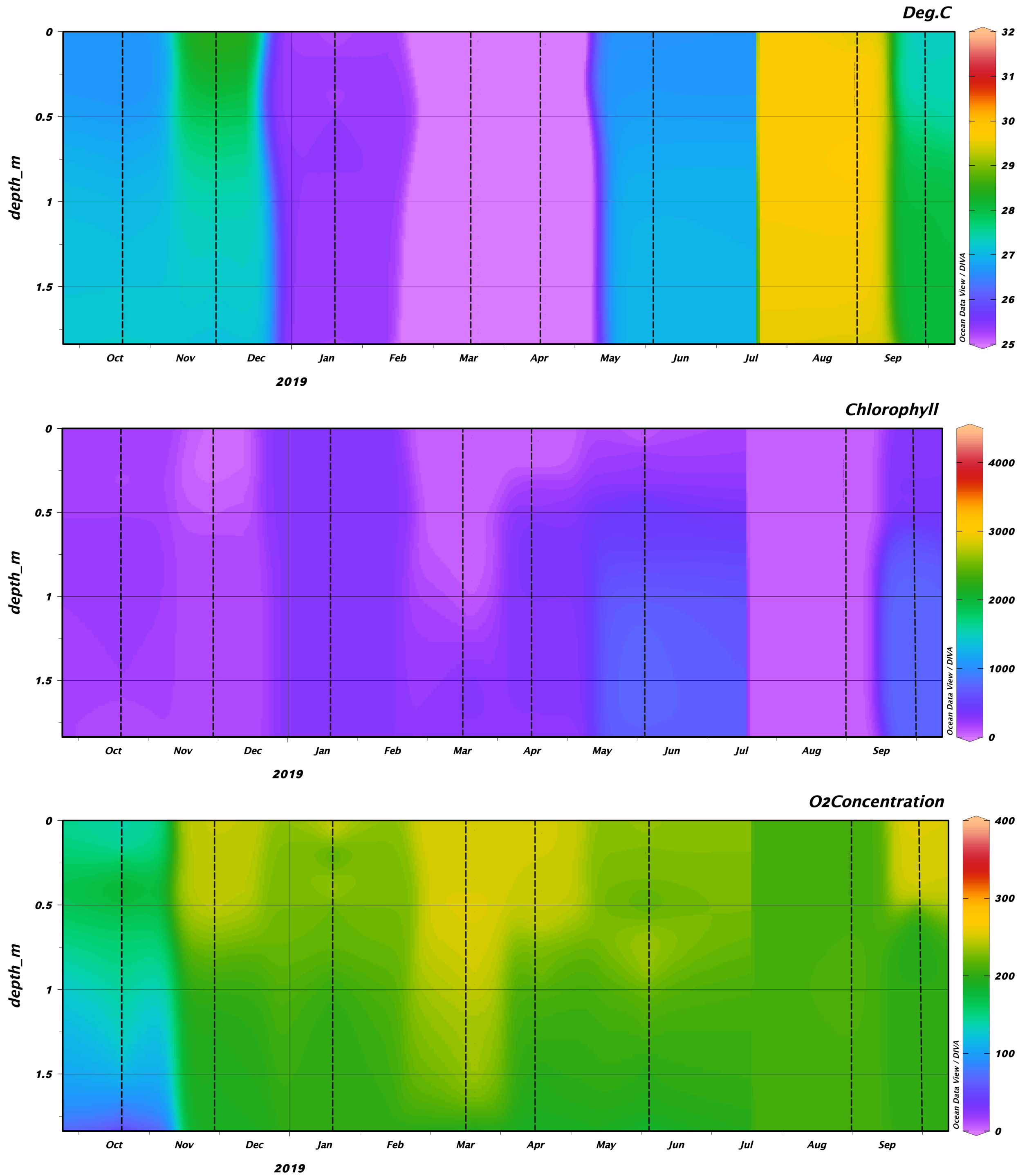

Fig. 3.10: Time-series plot at station 9, near the canal mouth. Dashlines mark sampling dates.

3.2 Chemical conditions in canal

In addition to monitoring the physical conditions in the canal, characterizing nutrient distributions was one of the main objectives of this project. Inside the canal, nutrient samples were taken from 6 sites. The comparison of nutrient concentrations in the canal was done by plotting concentration of each nutrient measurement across the length of the canal in a similar fashion to illustrations of physical conditions in the canal (fig 3.11, 3.12, 3.13, 3.14, 3.15, 3.16, 3.17, 3.18). The results were grouped by sampling date to document variations of nutrient concentrations. One exception for documenting nutrient concentrations occurred on 6/4/2019. The peristaltic pump was malfunctioning in the field, no discrete water sample was taken on that date.

Additionally, the mean value of nutrient concentrations at each site was plotted across the length of the canal for the reference of general nutrient distribution in the canal. From the mean values of nutrient concentrations, several apparent trends of spatial distribution were observed (fig 3.11). Firstly, nutrient concentrations are generally higher near the dead end of the canal, with the exception of ammonia. The spatial distribution of ammonia showed greater variability comparing to all other nutrients, especially in ammonia concentrations in the bottom water of the canal. This may suggest the origin of nutrients in the canal since the nutrient concentrations decrease with proximity to more oceanic sampling sites. Secondly, nutrient concentrations are generally higher in surface water samples, with the exception of ammonia concentration. This may reinforce the observations of origin of nutrients as the canal was generally well-stratified. The other common feature from the general trend of nutrient distribution is observed near site 5, where the Mānoa-Palolo drainage connects to the canal. This site is significantly shallower than other sites due to sediment accumulation. At site 5, nutrient concentrations including TP, Phosphate, and Nitrate/Nitrite are higher in bottom water (fig 3.11).

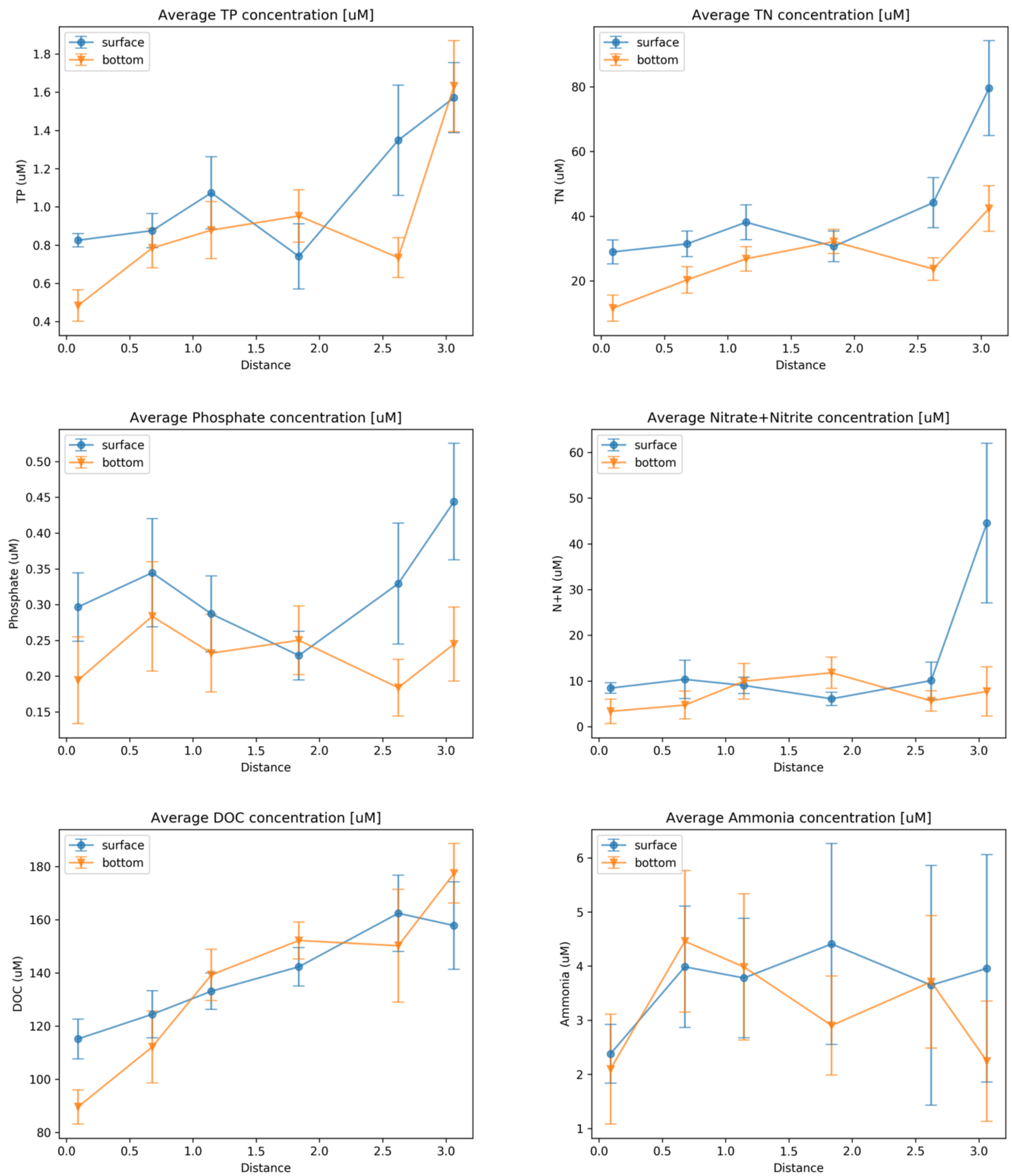

Fig 3.11: Mean values of nutrient concentrations across the length of the canal over the entire sampling period (n=8). Mānoa-Palolo drainage connects to the canal at 1.8 km from the mouth.

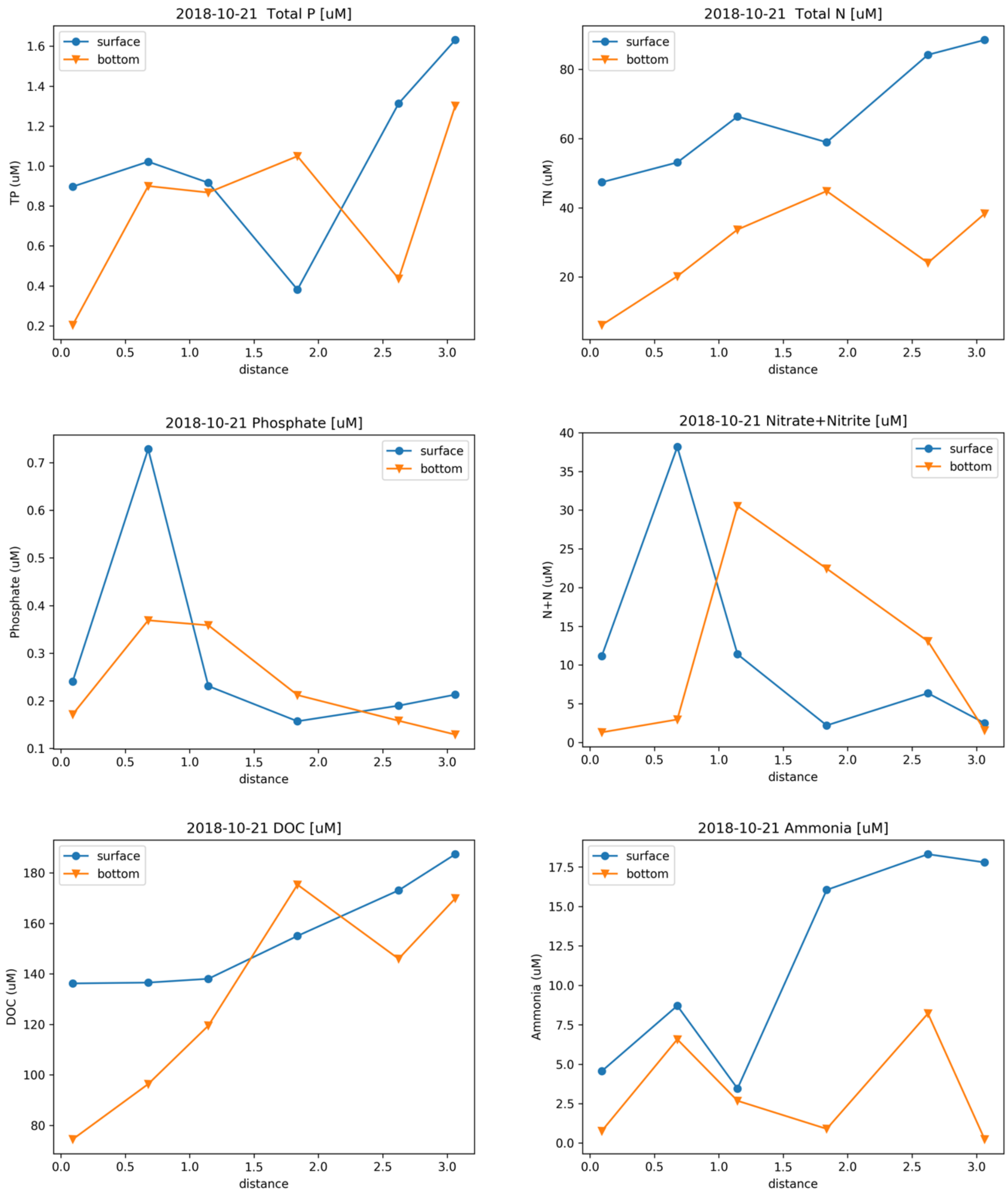

Fig 3.12: Nutrient concentrations across the length of the canal on 10/21/2018.

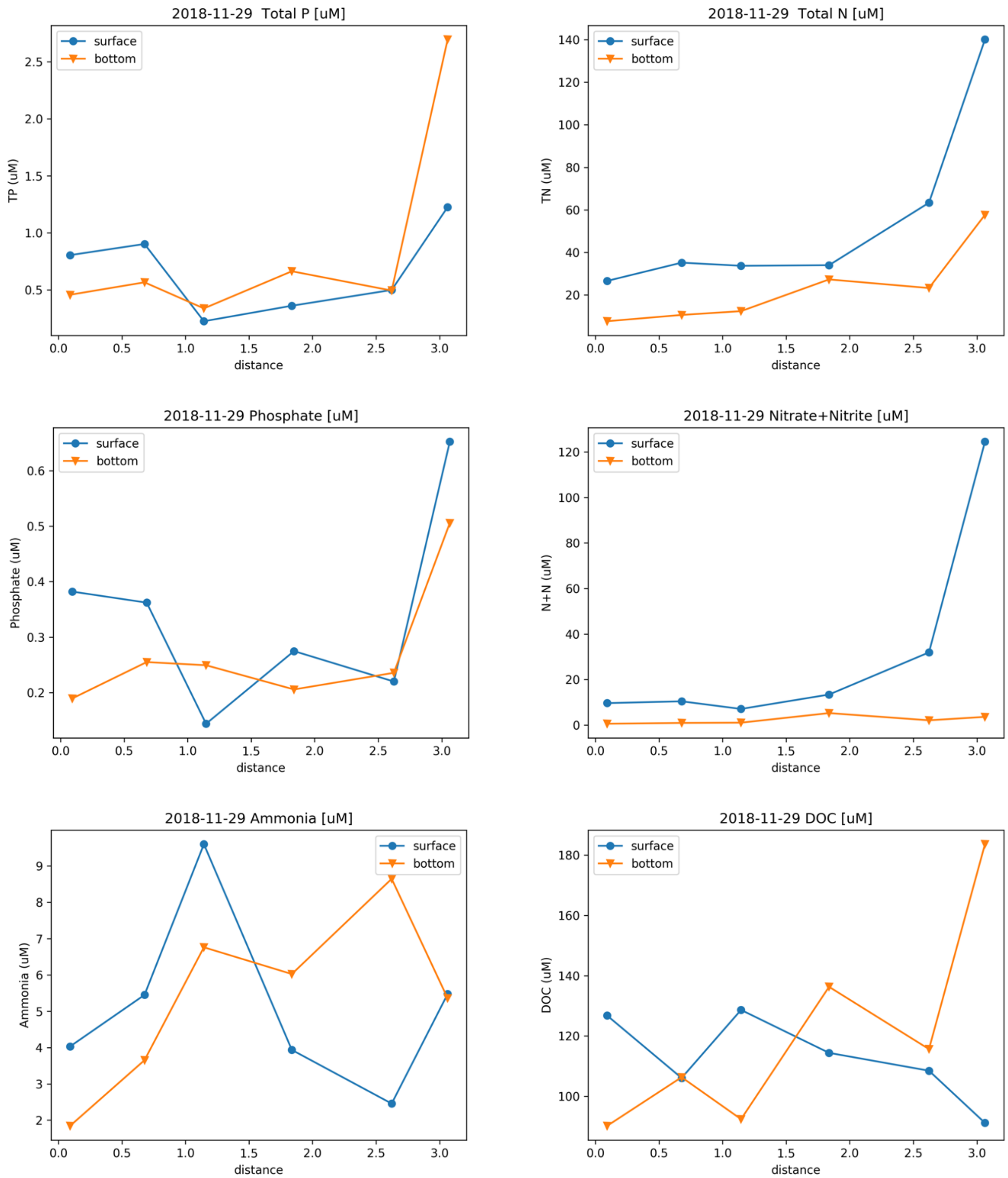

Fig 3.13: Nutrient concentrations across the length of the canal on 11/29/2018.

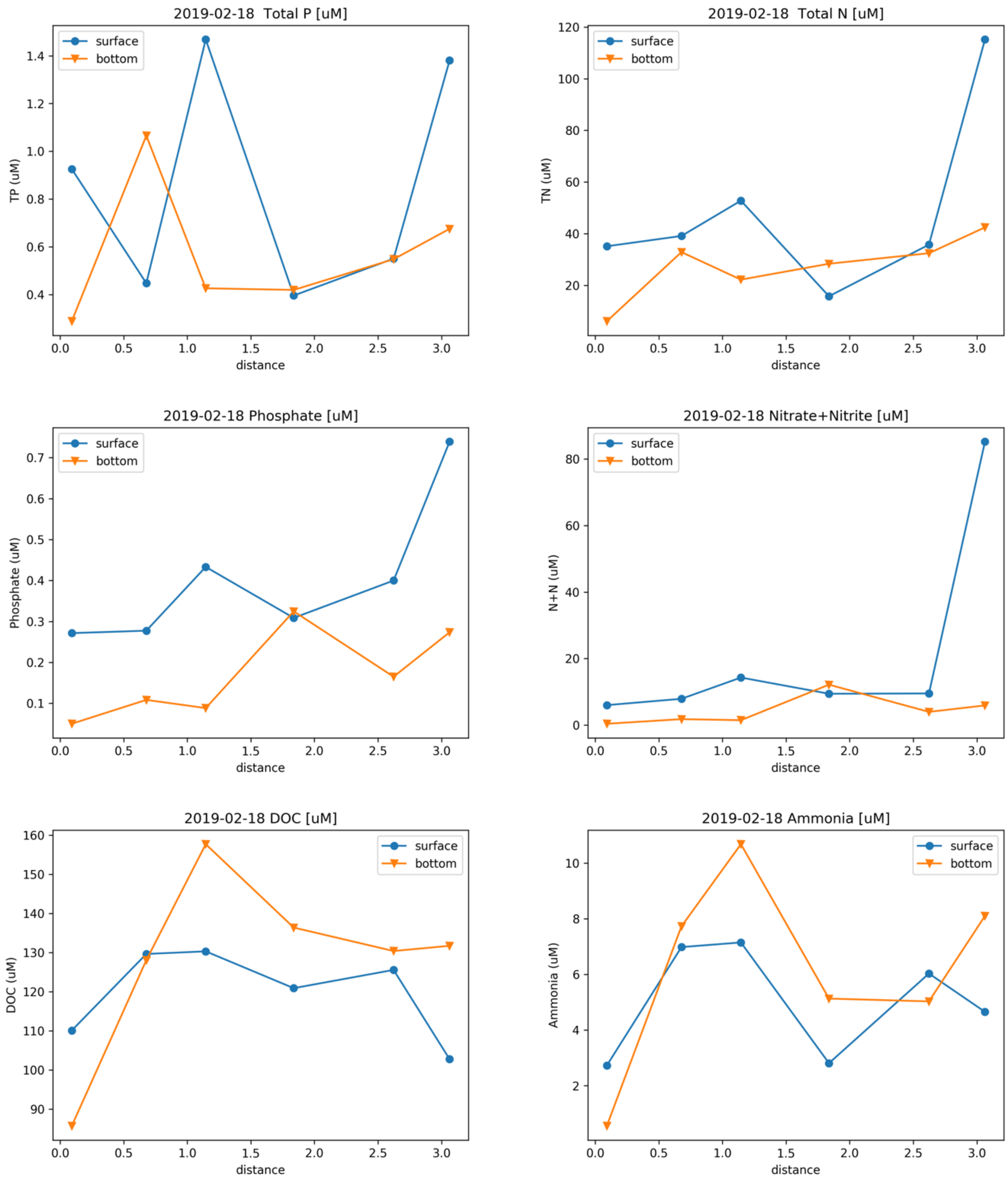

Fig 3.14: Nutrient concentrations across the length of the canal on 2/218/2019.

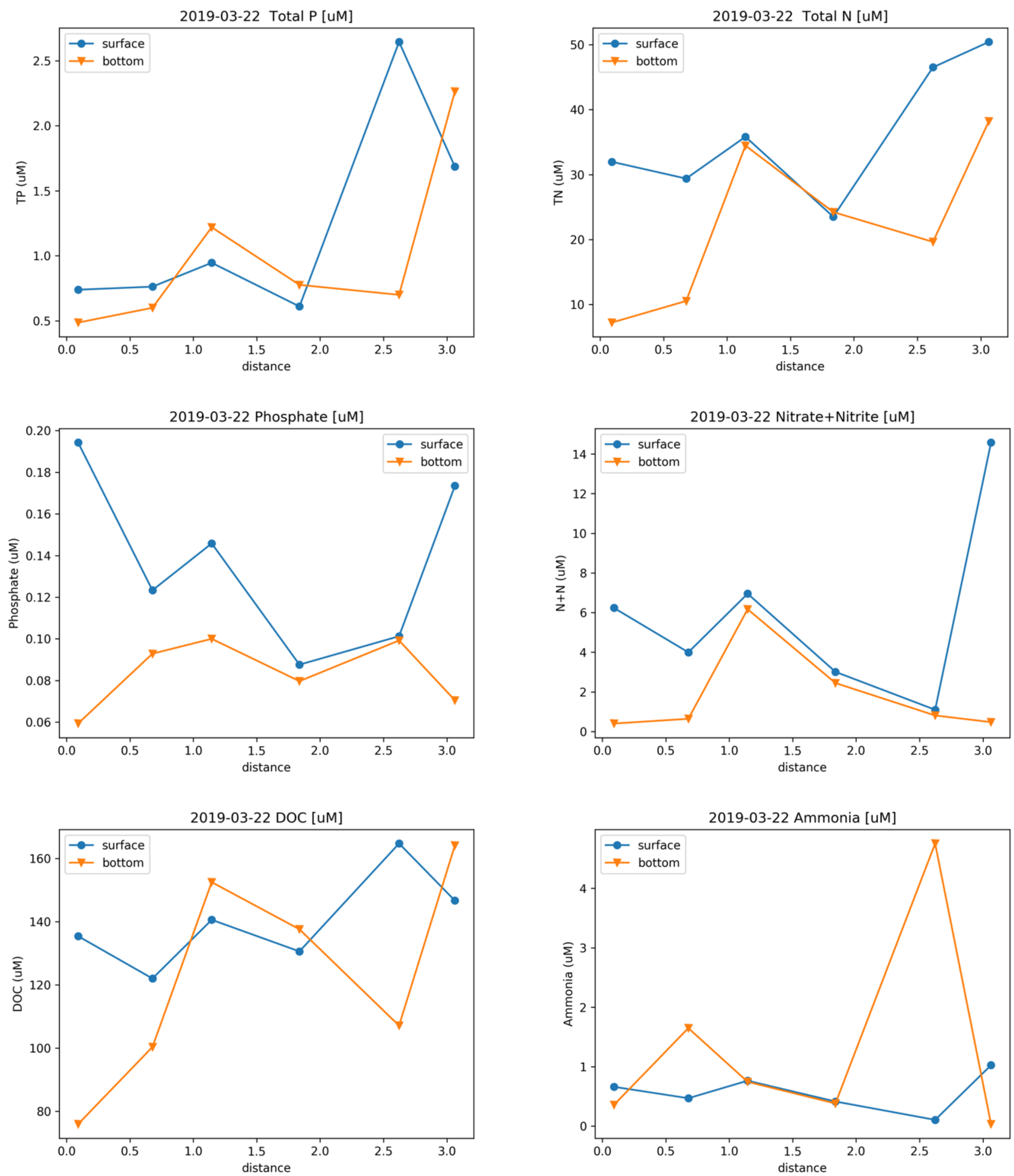

Fig 3.15: Nutrient concentrations across the length of the canal on 3/22/2019.

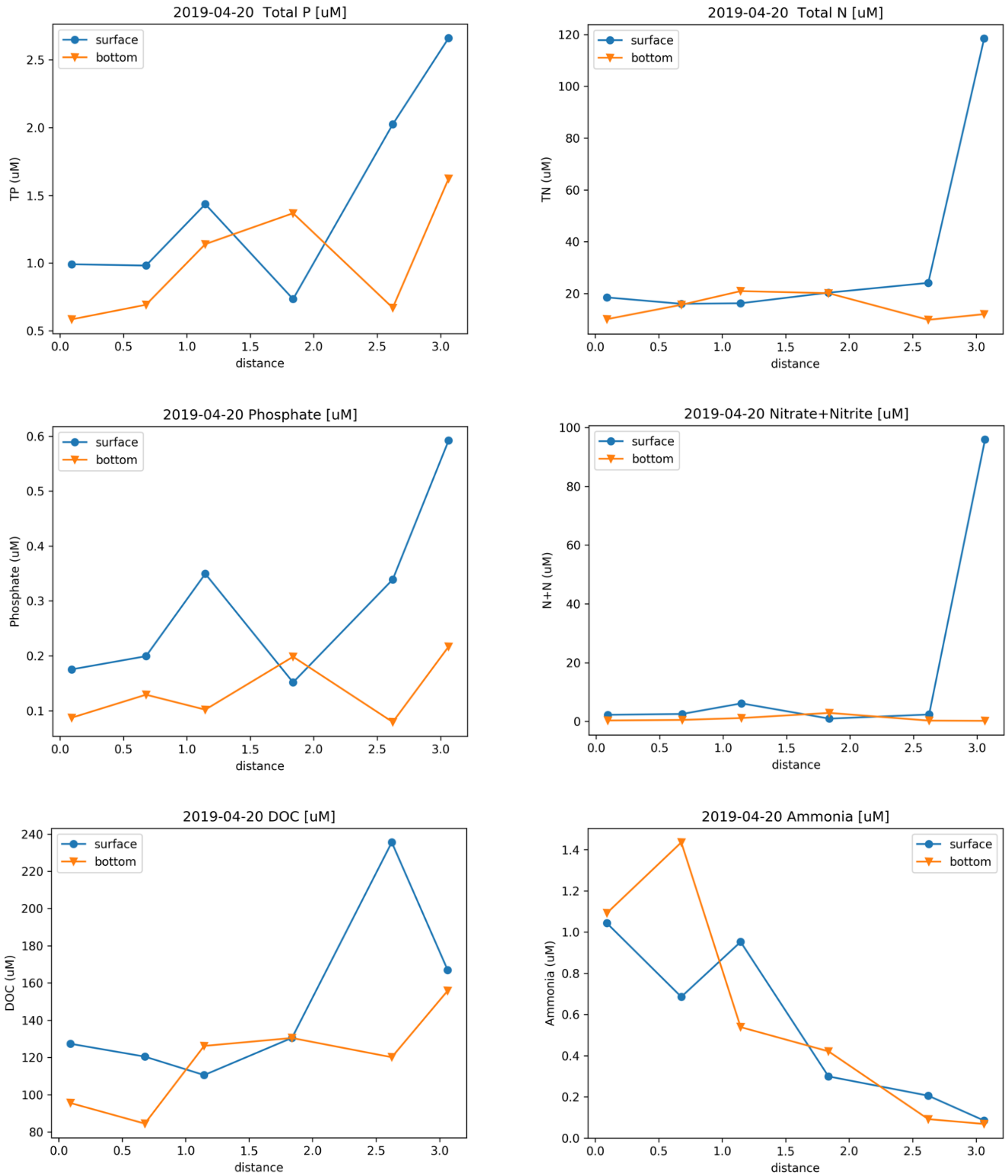

Fig 3.16: Nutrient concentrations across the length of the canal on 4/20/2019.

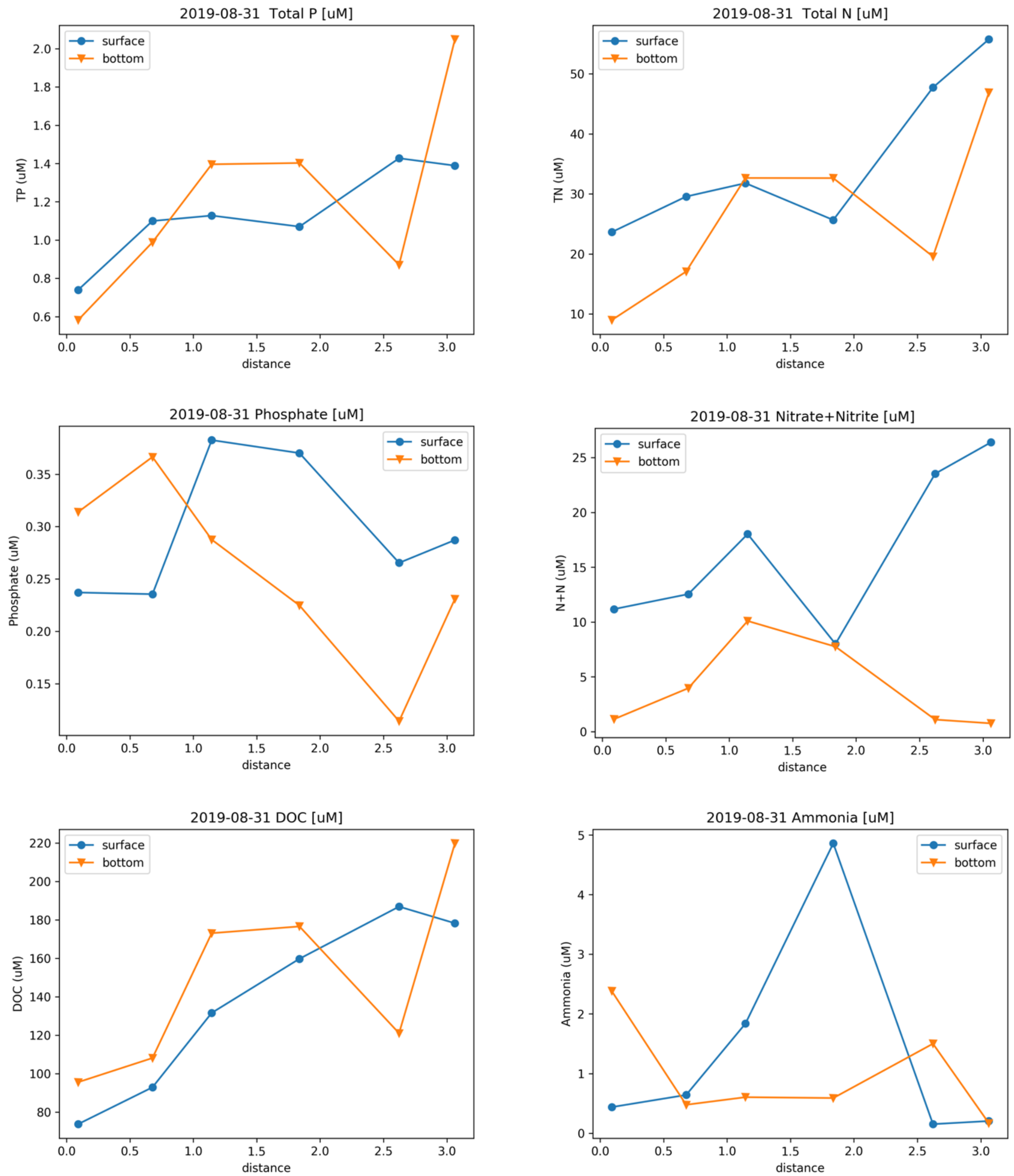

Fig 3.17: Nutrient concentrations across the length of the canal on 8/31/2019.

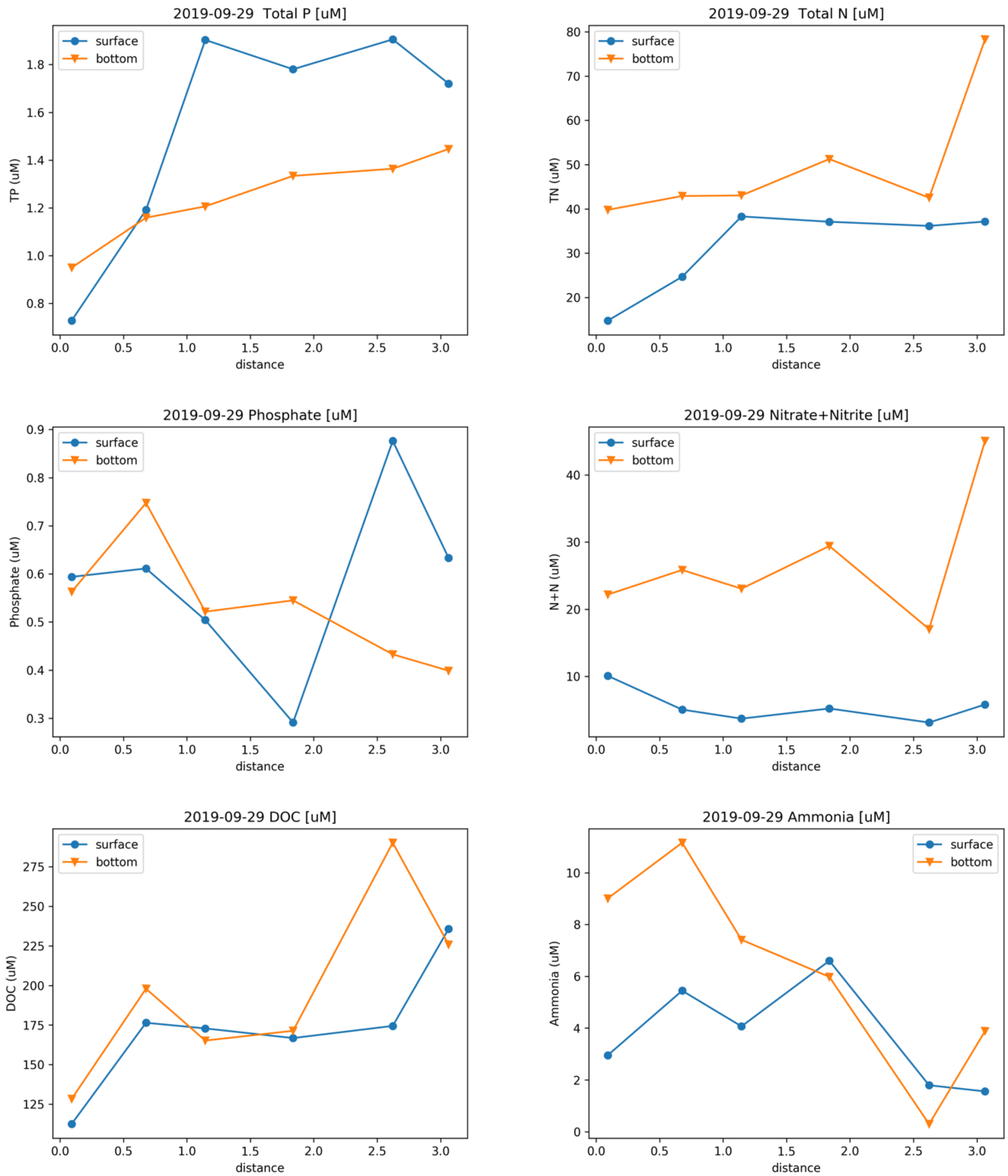

Fig 3.18: Nutrient concentrations across the length of the canal on 9/29/2019.

3.3 Physical and chemical conditions in the watershed

One of the main objectives of a water quality survey in the Ala Wai watershed was to identify the spatial variation of nutrient fluxes into the canal. In addition, to characterize the origin of nutrient fluxes into the canal, this project also tried to characterize the spatial variation in water quality in the three main streams. The mean values of discrete water sampling over the entire sampling period were plotted on overlaying maps to illustrate the general trend of water quality parameters in the watershed. In addition to the average conditions of streams, time-series data of each site was provided for comparisons. The time-series data were grouped together by their proximity and their affiliated streams. Over the entire sampling period, seasonality is especially pronounced in the upper Mānoa stream sites (‘W1’,’W2’,’W3, and ‘W4’). The pH value showed significant variability from site to site (fig 3.21). Trends and correlations between nutrients were not apparent, which may be a result of the environmental setting at each site. For example, the site ‘W1’ was in more pristine condition while the site ‘W11’ was a completely artificial concrete channel.

There are a few more general trends observed in the watershed, including the distribution of TN and TP concentrations. On average, the highest TN concentration was observed in Palolo stream at the site ‘W10’, while the highest TN concentration was observed in Makiki stream at site ‘W8’ (fig 3.22). Temperature also showed a decreasing trend toward the downstream sampling stations. However, a consistent temperature anomaly was observed at site ‘W11’ (fig 3.19). The mean temperature value was 27.4°C while the mean temperature value of all other sites 20.6°C to 23.4°C. In addition to the temperature anomaly, the highest DO and pH were also observed at site ‘W11’ (fig 3.33). The mean pH value at the site ‘W11’ was 9.2, with the highest value being 9.79. The supersaturation of DO was consistently observed at ‘W11’ as well (fig 3.33).

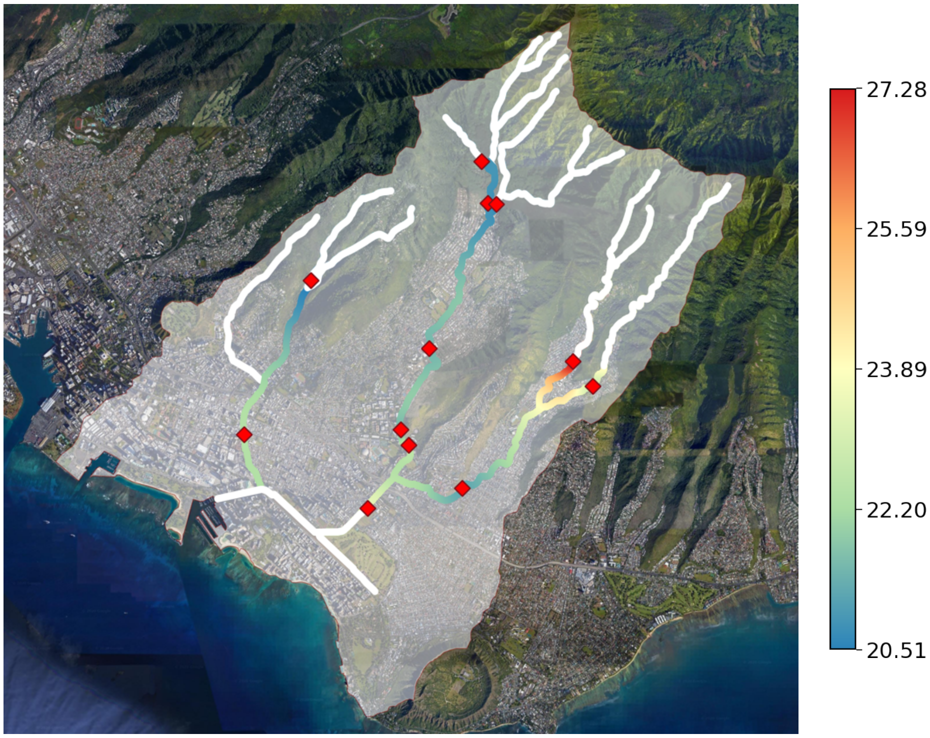

Fig 3.19: Mean values of temperature measurements in Ala Wai watershed, red dots marks sampling sites.

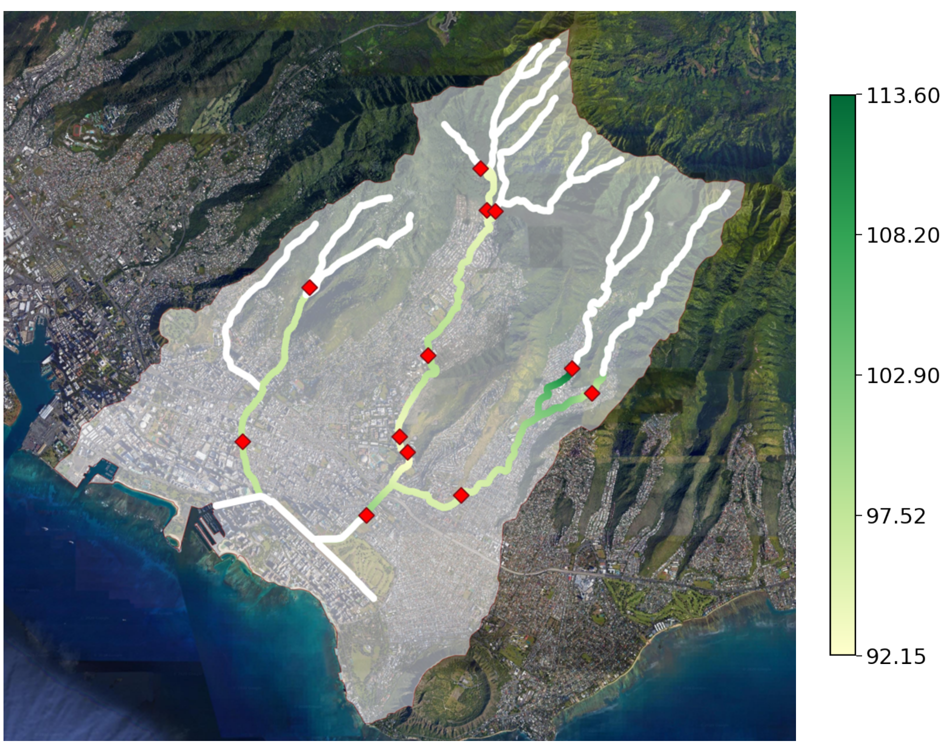

Fig 3.20: Mean values of temperature DO concentrations in Ala Wai watershed.

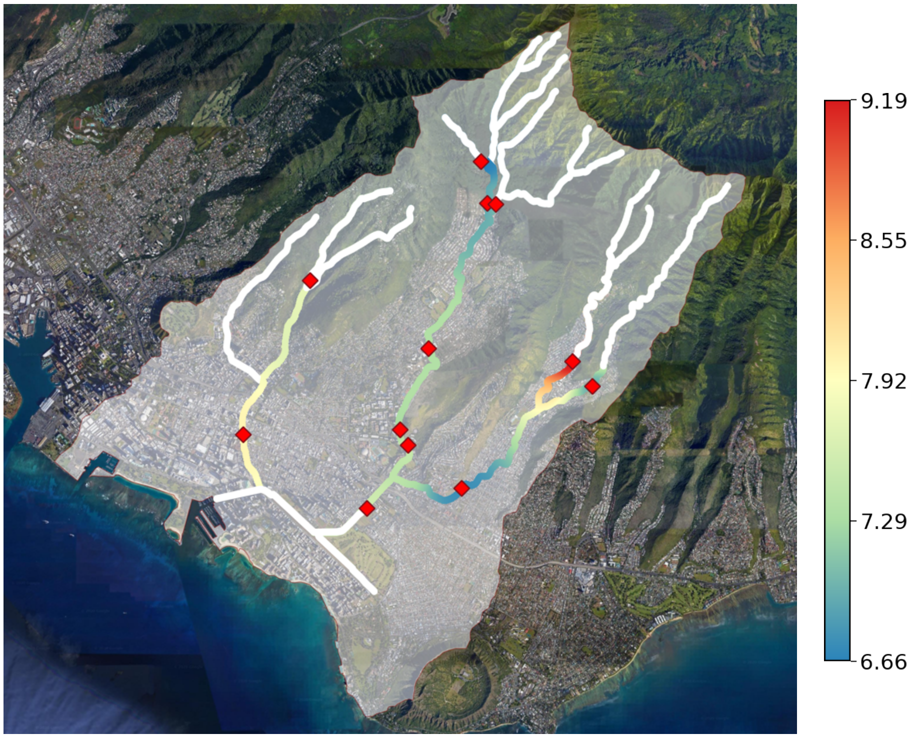

Fig. 3.21: Mean values of pH measurements in Ala Wai watershed.

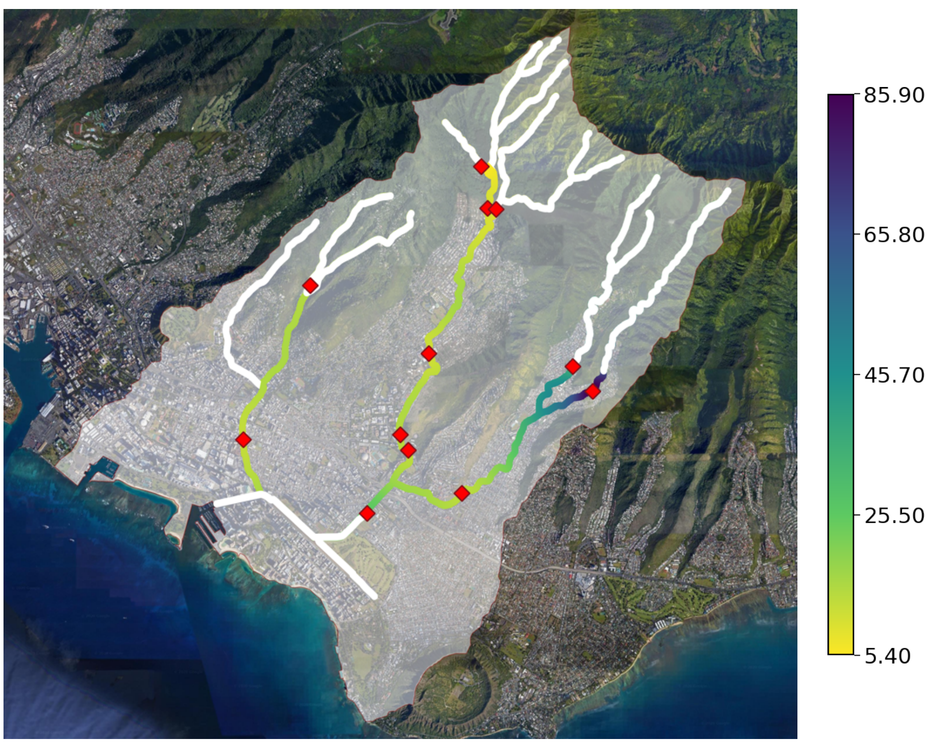

Fig. 3.22: Mean values of TN measurements in Ala Wai watershed.

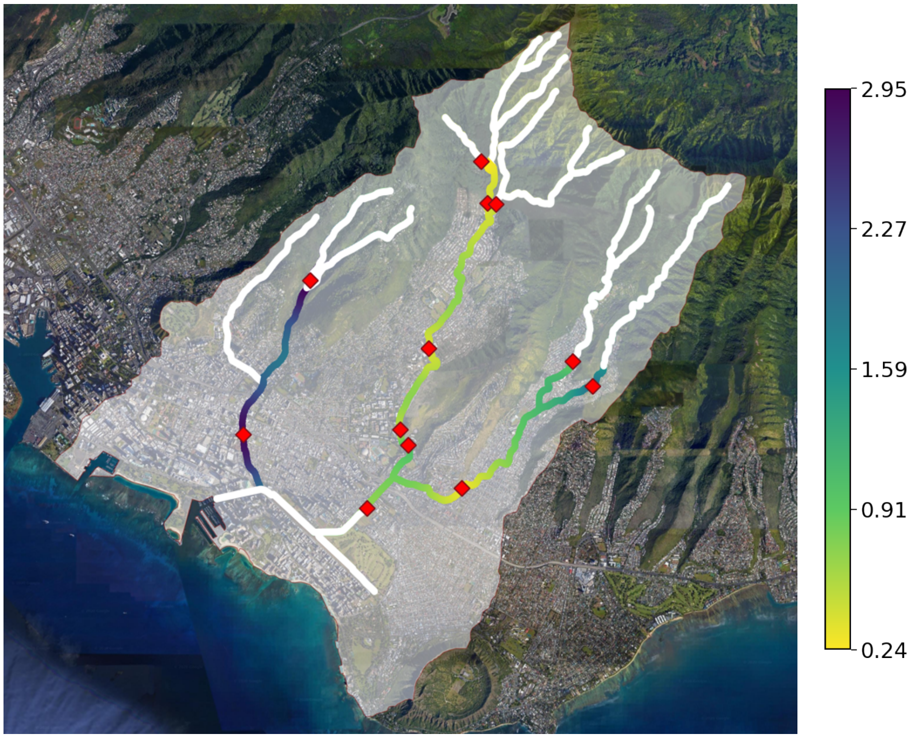

Fig. 3.23: Mean values of TP concentrations in Ala Wai watershed.

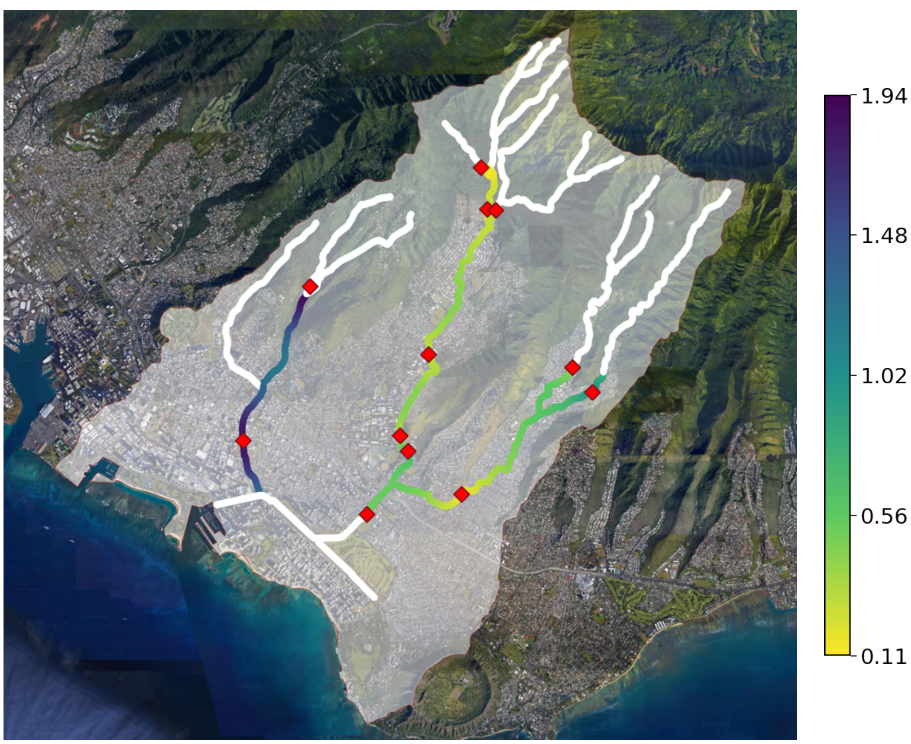

Fig. 3.24 Mean values of phosphate concentrations in Ala Wai watershed.

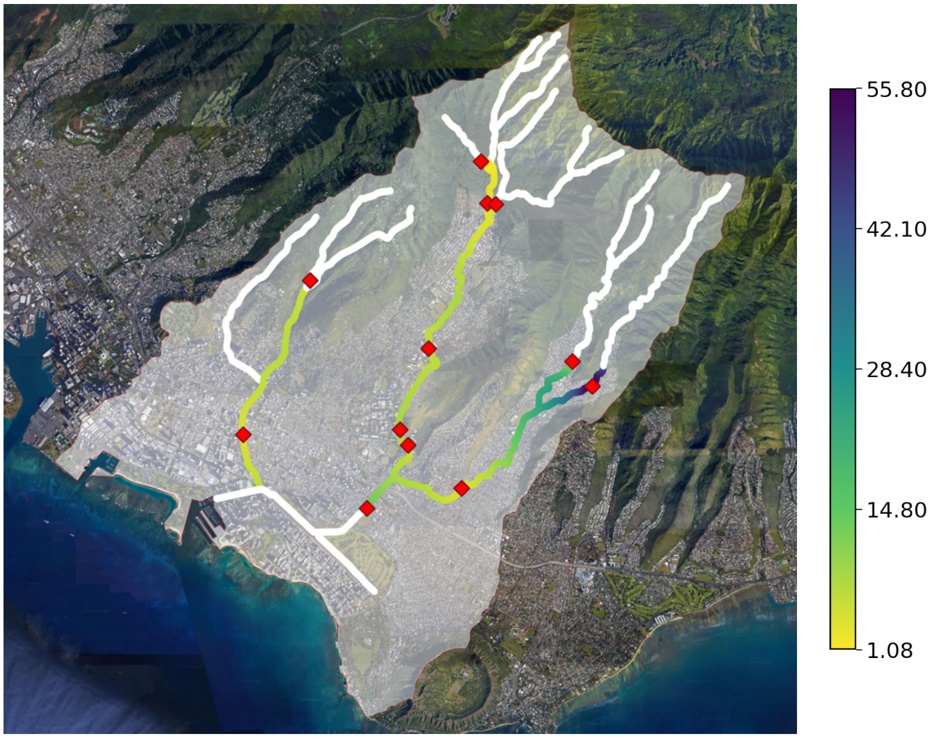

Fig 3.25: Mean values of nitrate + nitrite concentrations in Ala Wai watershed.

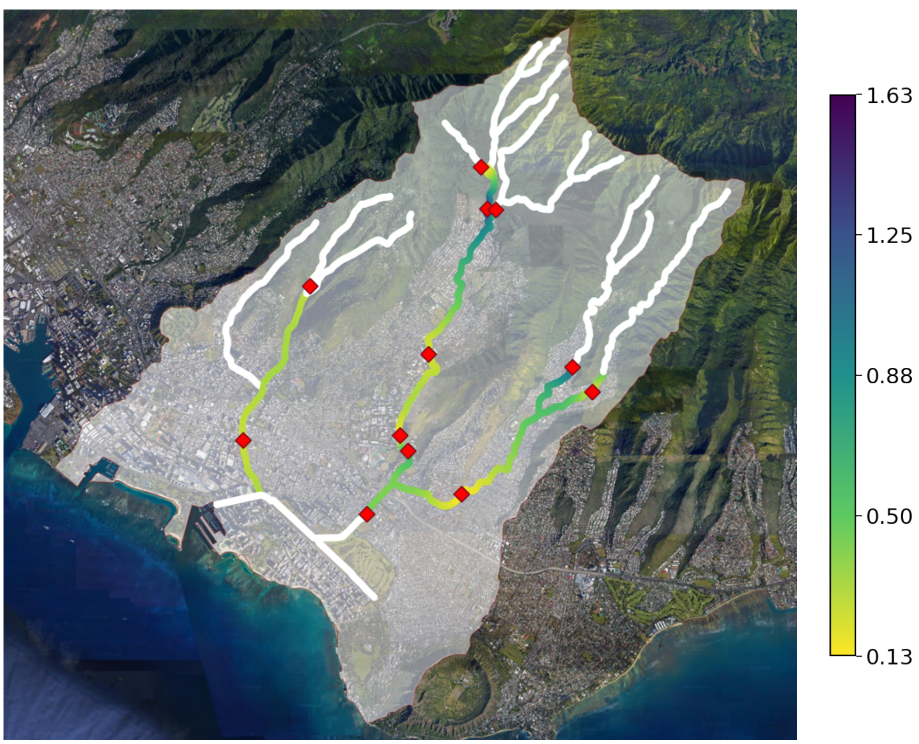

Fig. 3.26: Mean values of ammonia concentrations in Ala Wai watershed.

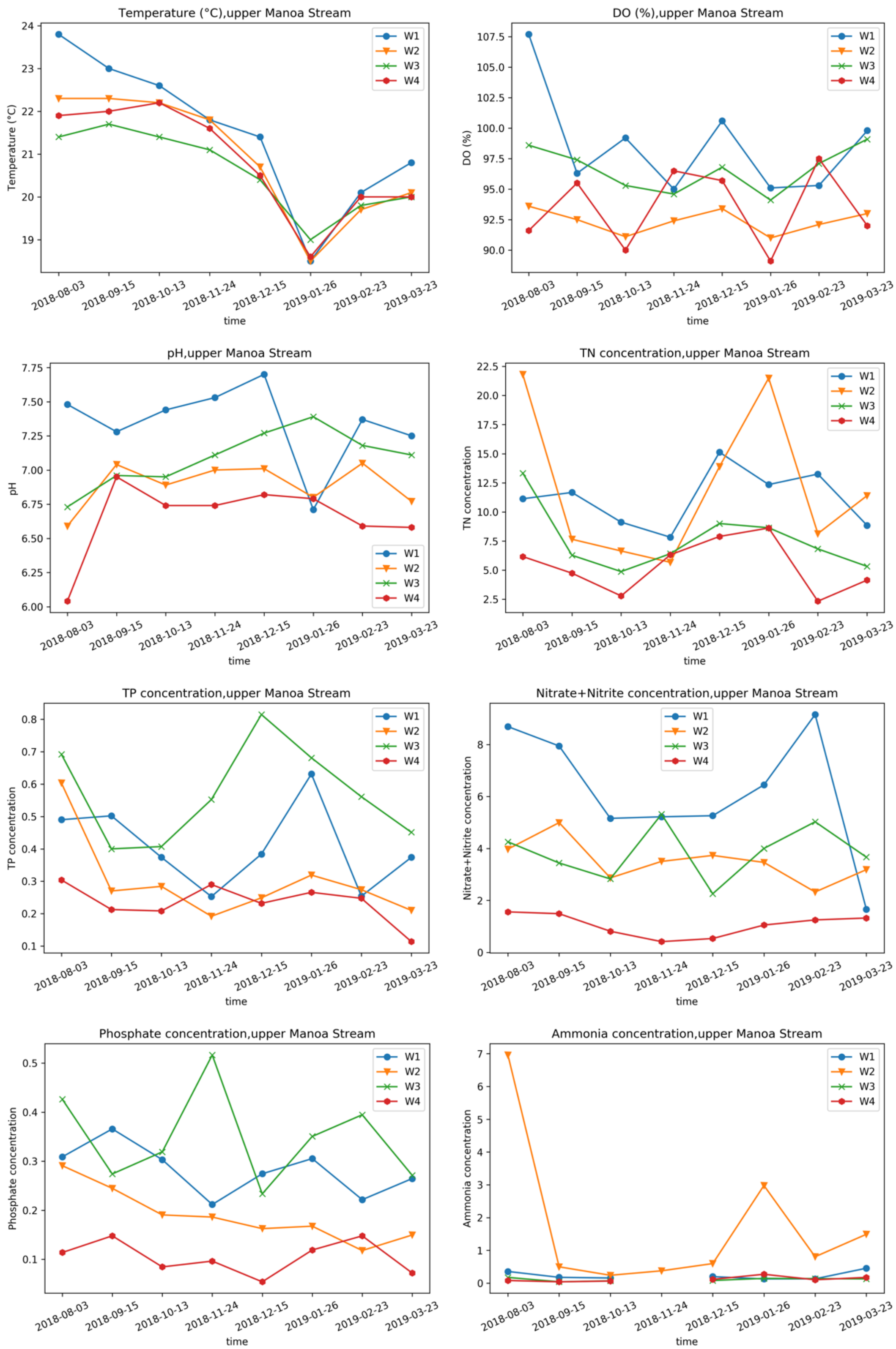

Fig 3.27: Physical (Temperature, DO) and chemical time-series of upper Mānoa stream (site 'W1','W2','W3','W4').

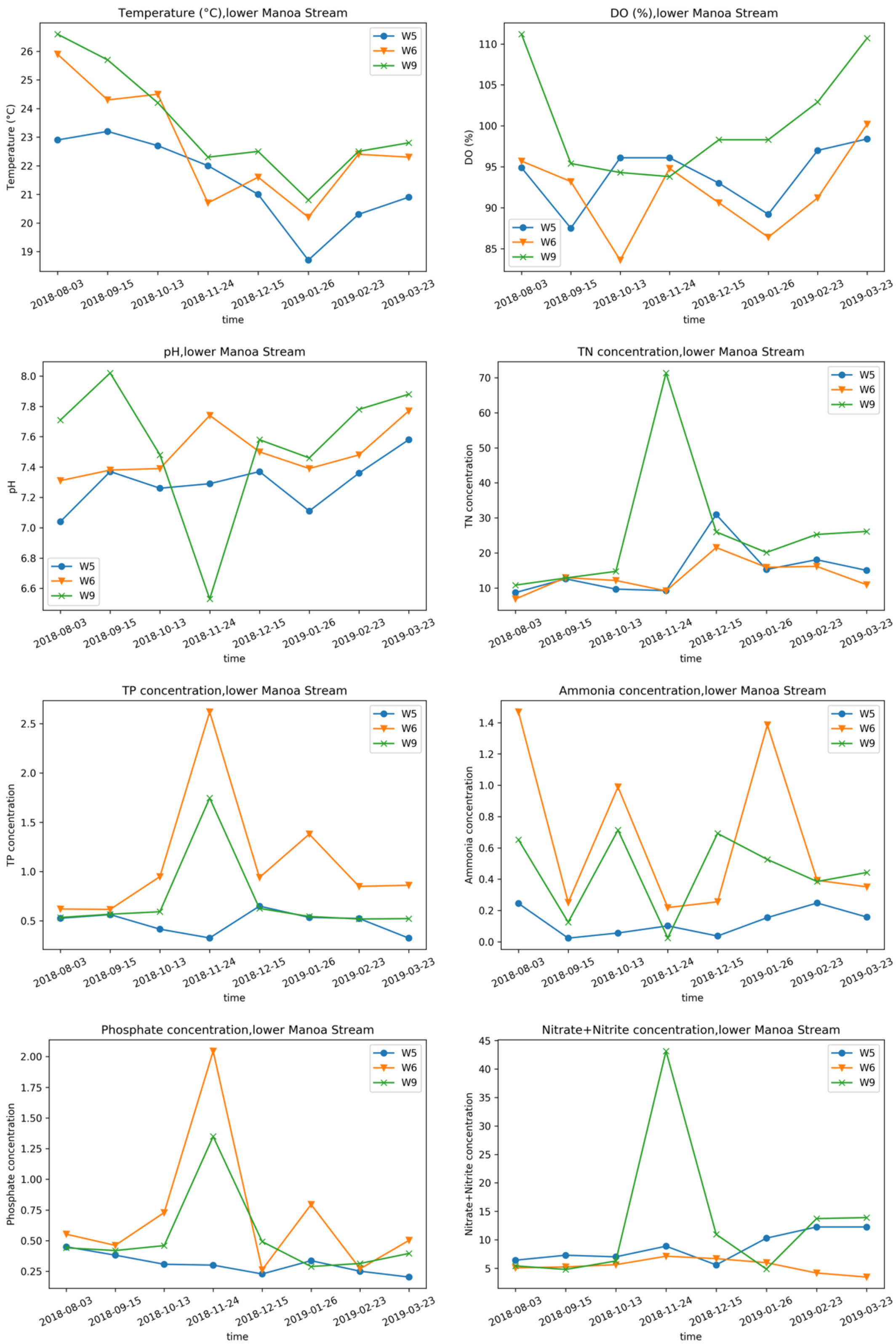

Fig 3.28: Physical (Temperature, DO) and chemical time-series of lower Mānoa stream (site ‘W5’,’W6’,’W7’).

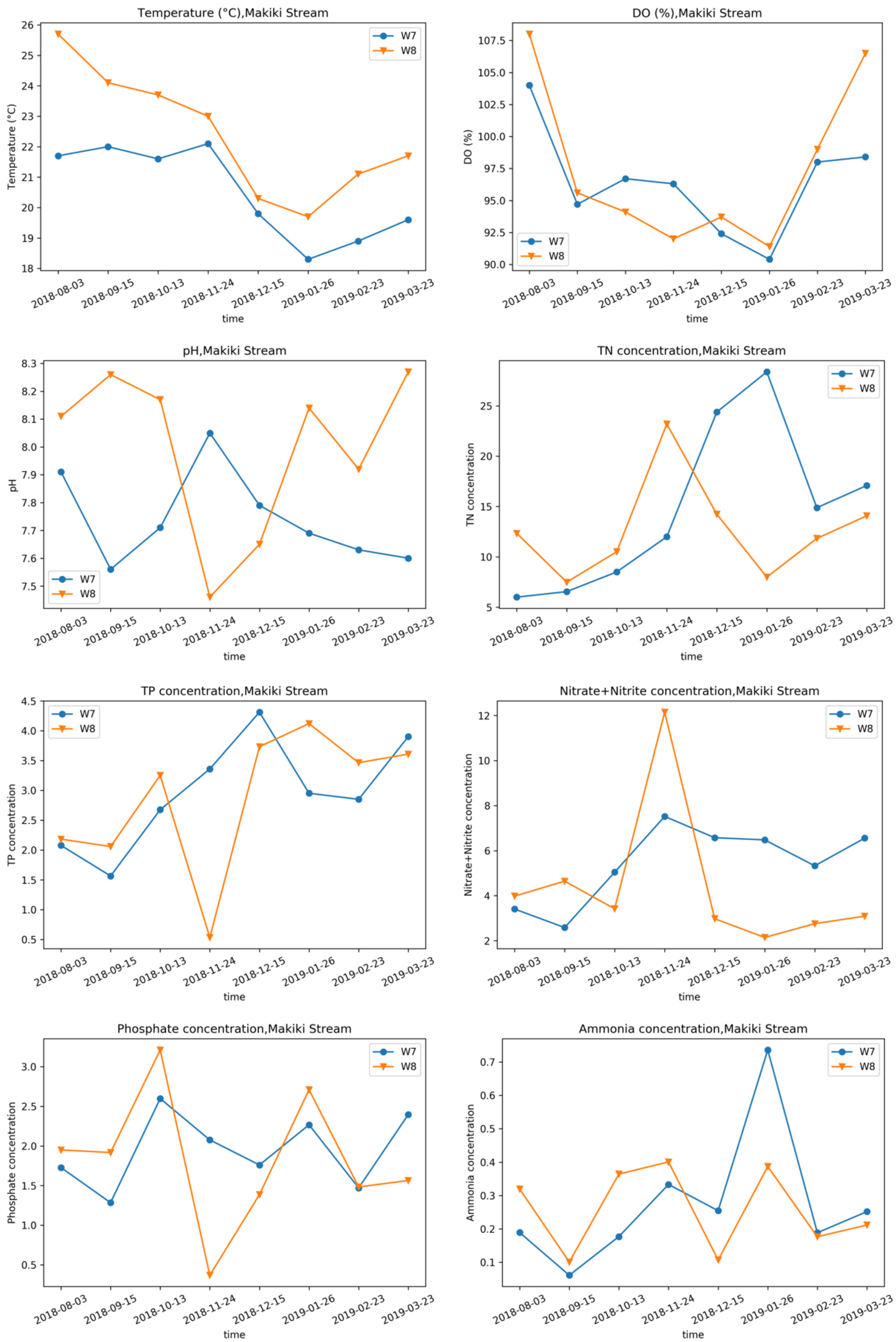

Fig 3.29: Physical (Temperature, DO) and chemical time-series of Makiki stream (site 'W7', 'W8').

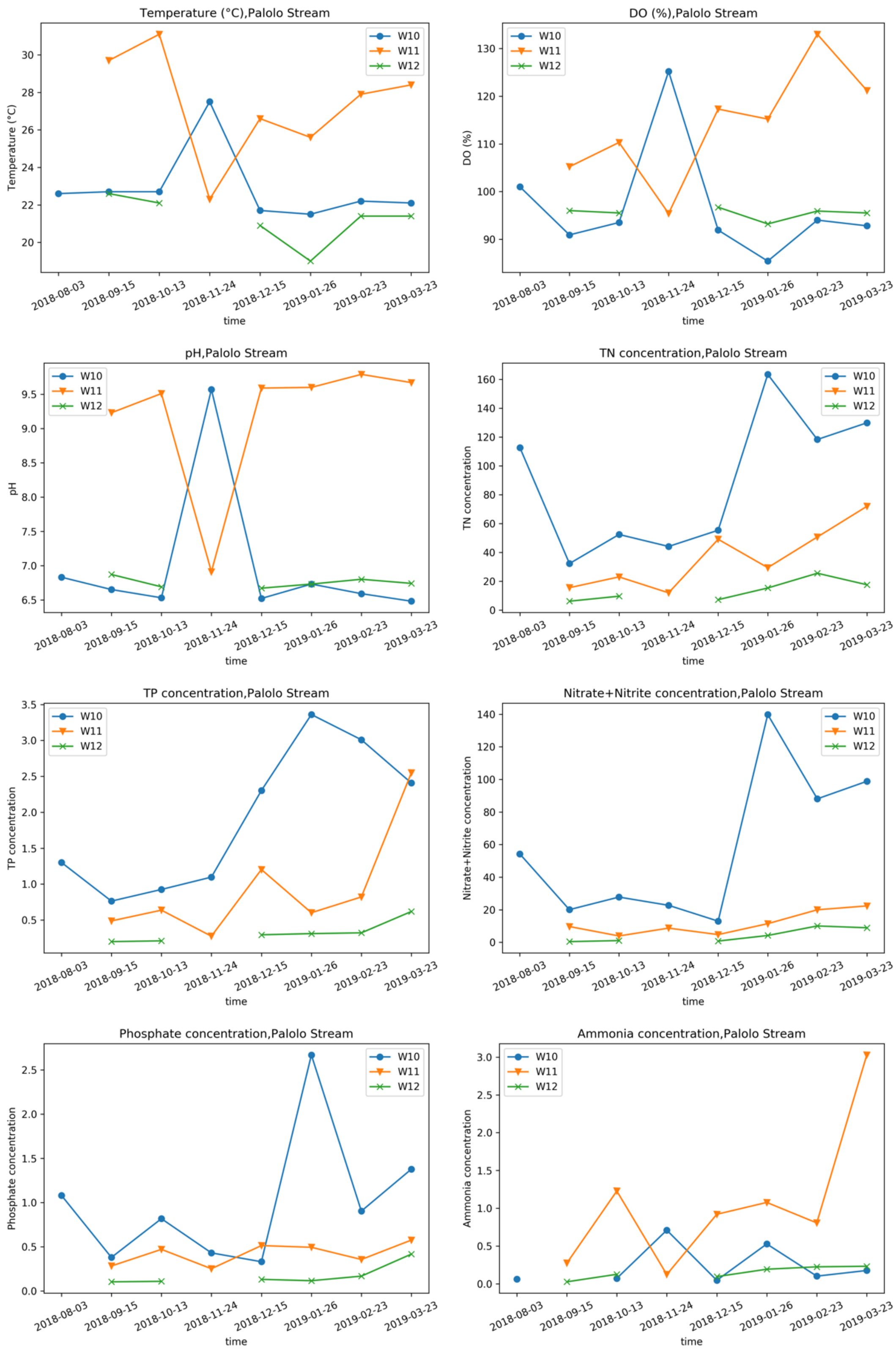

Fig 3.30: Physical (Temperature, DO) and chemical time-series of Palolo stream (site 'W10','W11','W12').

3.4 Correlations of physical and chemical conditions

Along the with monitoring of water quality and environmental conditions, this project also attempted to explore the correlation between physical and chemical forcing on water quality. To understand and quantitatively evaluate water quality parameters, Spearman correlation analysis was utilized to statistically identify any correlation between observed parameters. The Spearman correlation analysis ranked the strength of each set of parameters from -1 to 1. A correlation ranking of 1 suggested a strong correlation when the chosen set of parameters increase monotonically. A correlation ranking of -1 also suggested a strong monotonic correlation, but the chosen set of parameters had a negative relationship in this case. A Spearman ranking of 0 suggested that the parameters were not correlated. The Spearman analysis also produced a p-value with each correlation ranking, which denoted the statistical significance. A set of parameters with a p-value lower than 0.001 is marked significant in the following analysis.

In the canal, two main trends of correlations were identified in the heat map. Firstly, negative correlation rankings were observed between salinity and all of the measured nutrient concentrations (fig 3.34). This observation reinforced the differences in nutrient concentrations between surface water and bottom water since the canal was generally well-stratified with salinity gradients. Secondly, among all measured nutrient concentrations, correlation ranking between chlorophyll and DOC concentration was the highest.

In the streams, parameters are found positively correlated but without statistical significance in most cases (fig 3.35). Yet, notably, TP and phosphate are found to be the only two nutrients that correlate with pH values with statistical significance, suggesting that phosphorus may be responsible for pH values in the streams. In addition, pH was the only parameter correlated with DO that has statistical significance.

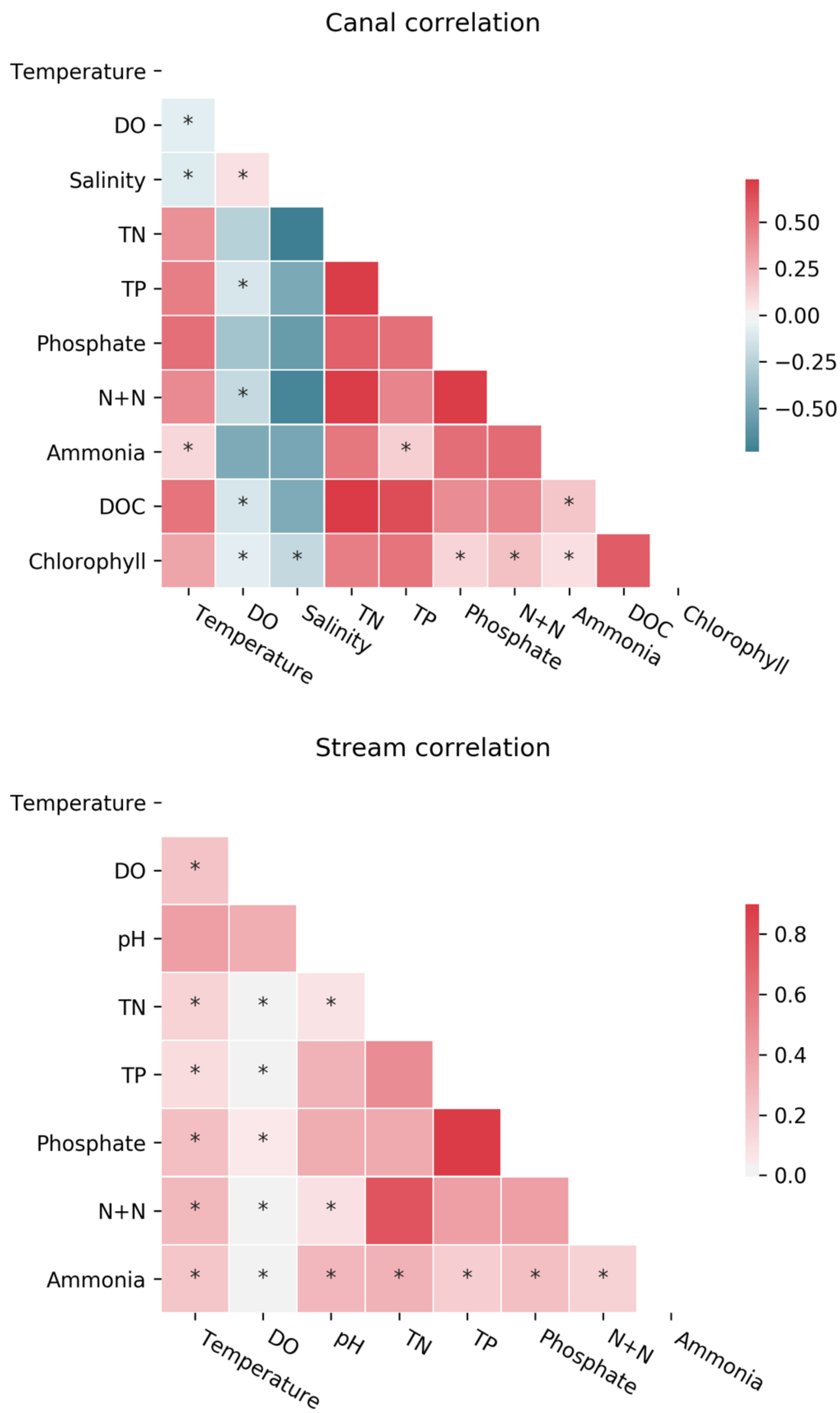

Fig. 3.31: Spearman correlation analysis of measured water quality parameters.

Correlation without significance (p > 0.001) are marked with *.

3.5 Estimation of water budget and nutrient fluxes– a simplified model

The water budget was calculated with the mean discharge rate of the Makiki drainage at the site 'W8' and Mānoa-Palolo drainage at site 'W9'. The result of the water budget and nutrient flux as described in Chapter 2 were summarized in the following tables (table 3.1, 3.2). The results showed that the Makiki stream was responsible for over 20% of phosphorus input despite only contributing to less than 10% of water budget in the canal. On the other hand, Mānoa and Palolo streams contribute approximately 97% of Nitrogen flux into the canal. The estimation of canal consumption represents the net effects of various nitrogen and phosphorus cycling processes. One assumption was made for the estimation of nutrient export. Firstly, this general estimation assumed that the canal has a uniform outflow across the stratified water column. Therefore, the nutrient concentration of the outflowing water was calculated by a volume-weighted average. However, in reality, the stratification of the water column could affect the estimated concentration of nutrient export; the effects are discussed in the following sections.

Table 3.1: Water budget and fluxes of the canal

Canal Volume (m^3)	Annual precipitation (mm)	Estimated evaporation (mm day^{-1})	Makiki discharge (m^3 s^{-1})	Mānoa-Palolo discharge (m^3 s^{-1})	Estimated outflow (m^3 s^{-1})	Estimated residence time (day)
258331	636.0±54.4	6.460±0.3	0.057±0.009	0.744±0.080	0.789	3.79

Table 3.2 Estimation of nutrient fluxes

	Makiki input *kg yr^{-1}	Mānoa-Palolo input *kg yr^{-1}	Canal output *kg yr^{-1}	Net system flux kg yr^{-1}
Total N	228.59±60.35	8519.12±1249.30	6594.85±1466.55	-2152.86
Total P	159.94±23.41	513.87±109.12	505.97±63.65	-167.84
$NO_2^- + NO_3^+$	83.19±21.58	4236.03±1489.67	1769.55±727.58	-2031.95
Ammonia	4.89±0.81	146.43±29.93	719.28±226.90	+567.96
Phosphate	101.62±16.99	378.78±89.29	163.38±34.21	-317.02
DOC	**N/A	**N/A	31627.67±3300.69	

*kg was converted base on molar mass of the element (i.e. N, P, C).
**DOC was not measured in stream samples.

4.0 DISCUSSION

The main goal of this study is to provide a quantitative understanding of the Ala Wai canal as an estuarine buffer between the urban watershed and the coastal tropical ocean. The canal consists of two major freshwater inputs and an outlet, making it a well-constrained, enclosed system for quantitative estimations. Findings in response to this research goal are categorized into the following: summary of conditions in the canal, and estimation of nutrient fluxes.

4.1 Summary of conditions in the canal

With the results generally aligned with previous studies, the canal is usually stratified with strong salinity gradients (Laws, 1993b). Episodic mixing can happen when wind, precipitation events, and excessive discharge provide the needed energy to break the gradient and provide turbulent mixing within the Canal (Scully, Friedrichs, & Brubaker, 2005). The previous study shows that during a storm event, excessive discharge can increase the extent of the surface freshwater layer. However, in this study, it is difficult to disentangle the contribution of the wind, precipitation, and stream forcing as a storm event usually provides all three of them. The enhanced mixing by excessive discharge and wind can be observed on 10/21/2018, 4/20/2019, and 9/29/2019/. On these sampling dates, the freshwater layer (0 PSU) is replaced with brackish water. The other noteworthy feature of the excessive discharge is observed in surface salinity, which shows that the freshwater layer towards the back of the canal persists in those events (fig#). The persistent stratification in the back of the canal indicates the poor horizontal mixing of the canal as the result of sediment shoaling form the Mānoa-Palolo outflow. The hindered horizontal mixing also signifies that the canal can be divided into two sections when it comes to analyzing the water budget and nutrient transport. Nuss also pointed out that residence time of water can be much higher in the back of the canal (from the dead-end to Mānoa-Palolo drainage) comparing to the section towards the mouth. The average residence time of water is 3.79 days.

The canal is significantly shallower than previously reported. In Laws' 1993 report, the depth of the canal was about 1 meter deeper than the current observation, but the general features of canal bathymetry are fairly consistent. Our estimated canal volume is approximately 50% less than the reported volume in Law's 1993 study. A comparison of sediment accumulation rate with the reported rate of 8×10^3 m^3 yr^{-1} can be made by calculating the difference in canal volume. Assuming dredging projects restore the canal volume to its original state consistently every time throughout history (~5.84×10^5 m^3), the calculation gives a figure of approximately

20×10^3 m^3 yr^{-1} as the current sedimentation rate. Estimation can also be made by discounting the fact that the canal was dredged in 2002 and calculate the difference between 1993 and present, which gives a figure of 16×10^3 m^3 yr^{-1}. In both cases, the estimation of sediment accumulation rate is higher than the previous estimation, which indicates that the reduced volume needs to be taken into consideration during the estimation of biogeochemistry cycling and long-term prediction.

In terms of the general state of DO and chemical conditions, our results also align with previous surveys. The overall trend between nutrients and salinity also supports the observation of excessive nutrient input from the streams. The trend of nutrient concentrations also suggests that excess input combine with slower recirculation in the back of the canal facilitates respiration, explaining the anoxic condition of the bottom water. As an attempt to establish a relationship between productivity and nutrient concentrations with chlorophyll data, the relationship between nutrient concentrations and chlorophyll was largely variable even though the Spearman test suggests positive correlations.

Fig. 4.1 Surface salinity after excessive discharge on 10/21/2018.

4.2 Estimation of nutrient fluxes

For the fluxes into the canal, nutrient concentrations showed significant temporal variability, but the spatial comparison gave a clearer picture of water quality in the watershed. The Makiki drainage provides less than 10% of water inflow to the canal, but it brings in about 25% of TP flux. On the other hand, water from Mānoa-Palolo drainage has a much higher concentration of TN. The water quality survey also shows different hydrochemistry across different basins. Notably, the varying water quality parameters may be attributed to soil characteristics or the state of the streams (Rothwell et al., 2010). For example, the Palolo stream has different soil pH classification from Mānoa and Makiki watershed and the highest was also observed at a completely artificial section of Palolo (Soil Atlas Hawai‘i). The environmental setting greatly alters the physical and chemical characteristics of stream water.

Estimation of the nutrient fluxes in canal outflow can be rather complicated as tidal influence contributes to a more complex mixing process. In previous results, the estimation of nutrient export is based on a volume-weighted average of nutrient concentration through the entire water column. However, fluxes of DIN might be biased by the vertical gradients of flow and restricted mixing. The previous study shows that tidal forcing affects the outflow by 5-10% without much mixing (Nuss, 2016). To mitigate the bias, a new estimation can be made by adjusting the nutrient concentration of the outflow, assuming that the upper freshwater and mixed layer are responsible for nutrient export. This approach identifies the depth of the upper layer with an exponential regression of depth-salinity data, then calculates the new concentration by filtering out data points from the bottom, saltwater layer. The adjusted nutrient export is calculated and listed in the following table. It is important that net flux of all nutrients remains in the same direction. Unfortunately, this estimation is highly subjected to the mixing condition at the mouth of the canal. The episodic discharge and fluctuation of nutrient loading in stream waters contributes to the results as well, hence uncertainties in table 3.2 add up quickly to significant values. These two estimations give a general idea in regard to the canal’s nutrient retention capacity. As an estuary of such a small extent, most of its water is discharged into the ocean shortly after entering the system. The short residence time of water may contribute to the poor ability to sequester dissolved nutrients base on the adjusted flux. For comparison, Law’s 1993 report provides a net carbon flux out of the canal of approximately 131,400kg y^{-1}, which is smaller than our estimations.

Improvement of sampling and conceptual modeling are still needed for closing the nutrient budget of the canal. Firstly, as mentioned in the previous paragraphs, the canal can be divided into two sections due to the sediment accumulation. Nuss suggests that the back of the canal would have a recirculation speed much slower and the residence time of water is almost 4 times longer than the rest of the canal, even though its volume is approximately 50% of the canal volume. This suggests that future analysis can establish the dead end of the canal as an independent system, taking water input from Mānoa-Palolo drainage and recirculate the flow through the bottom. Because nutrient and chlorophyll concentrations are so much higher in the back of the canal, setting up an independent steady state may help for estimating the metabolism, nutrient fluxes, and the possible sulfide production in the anoxic sediments. However, a velocity or flow rate measurement will be needed to quantify recirculation. A flow rate measurement can also benefit solving nutrient fluxes near the canal mouth. Secondly, to estimate the storage of nutrients, sediment data, allochthonous input, and benthic metabolic activity will need to be included in future investigation.

Table 4.1 Adjusted canal nutrient export

	Adjusted export	change	Adjusted net flux	change
	kg yr^{-1}	%	kg yr^{-1}	%
TN	8670.07±1306.75	+31.46	77.64	-96.40
TP	600.88±50.60	+18.75	72.93	-57.55
$NO_2^- + NO_3^+$	2326.33±458.43	+31.46	1992.89	-1.93
Ammonia	761.01±154.06	+5.8	-609.69	+7.34
Phosphate	185.44±30.98	+13.5	294.96	+13.50
DOC	35306.61±3754.67	+11.6	N/A	

4.3 Eutrophication outlook

According to the metrics provided by 2008 National Estuarine Eutrophication Assessment report, the Ala Wai Canal can be categorized as highly eutrophic. The symptoms of eutrophication in Ala Wai Canal include poor water clarity, episodic anoxia, and episodic high chlorophyll concentration. Furthermore, the magnitude of nutrient flux into the Ala Wai Canal is among the highest in the nation (Bricker et al., 2008). For example, the TN and TP load into the canal per area, 32977kg km^{-2} yr^{-1} and 1959kg km^{-2} yr^{-1} respectively, are only matched by a few estuaries across the US; for a comparison, Potomac river in mid-Atlantic region is rated highly eutrophic with potential worsen conditions in the future, has TN input of 26805kg km^{-2} yr^{-1} and TP input of 1170kg km^{-2} yr^{-1}. The high level of eutrophication implies severe potential of algal bloom and enhanced anoxia in certain segments of the canal. Comparing to previous reports, we observed a higher rate of sediment accumulation and nutrient discharge. The higher rate of sediment accumulation in the canal implies the impacts of land use change in the Ala Wai watershed (Walling, 1999), while the higher nutrient discharge essentially prevents the improvement of water quality in the system.

The impact of increasing eutrophication has implications beyond the estuary. Estuaries serve an important role as buffer zone that can provide dilution for discharge (Laws, Ziemann, & Schulman, 1999). In some cases, estuaries can be nutrient sinks and protect coastal ecosystems from anthropogenic pollutions. In our case, due to the short flushing time, the coastal ecosystem is very vulnerable to nutrient discharge from the canal. On average, the canal shows some ability of nutrient retention, which is important at reducing the direct impact on the coastal water quality. With careful planning, the Ala Wai Canal can have the ability to remove more nutrient as a constructed wetland (Tanner, Clayton, & Upsdell, 1995). Enhancing nutrient removal by turning the canal into a constructed wetland with recirculating water and planting may have the potential to remedy poor water quality in the adjacent area (Ayaz, Aktaş, Findik, Akça, & Kinaci, 2012). However, restoration and management of the Ala Wai Canal also has to focus on flood control, which has increasing potential of destruction due to sea level rise, king tide events, and climate anomalies from global warming. The tight space and urban developments around the canal indeed pose serious challenges for controlling eutrophication and developing sustainable solutions.

5.0 CONCLUSION

In this study, empirical data of water quality was collected to provide a basis for spatial analysis. While the results provide a quantitative approach to understanding the Ala Wai Canal, the contributing fluxes from the streams and the outflow of the canal was highly variable. The nutrient concentrations vary greatly, resulting in significant variability in estimating the net flux of the system. The nutrient concentrations in the canal outflow are also highly variable, reflected by the high uncertainty from sample data. The uncertainty mainly stems from varying conditions of canal mixing and the magnitude of stream discharge. The stream water quality also provides contrary features of each watershed as the distribution of nutrients is quite different across three streams. For example, on average, TP concentration is 2.86 uM in the lower segments of Makiki drainage, approximately 4 times higher than TP concentration in the Mānoa-Palolo drainage. The observations in spatial gradients of nutrient contribution can be valuable references for future management efforts.

Despite the variability of quantitative analysis, the spatial trend of physical and chemical characteristics provides for more robust interpretation. The physical characteristics of the canal, including bathymetry, salinity-driven stratification, DO, and chlorophyll concentration in the canal generally agree with previous studies. The comparison with previous studies points out that the sediment accumulation rates may be much higher in the canal. The consistent physical conditions suggest that current management methods for water quality and resource allocations are not sustainable. The fundamental concerns of the Ala Wai Canal remain largely intact. In addition to physical conditions, the canal shows some ability of nutrient retentions. The previous study points out that the Ala Wai Canal is extremely heterotrophic, however, the comparison of the metabolic state is not available due to the lack of measurement of respiration and photosynthesis. Incubation measurement can assist the understanding of the average biological nutrient usage in the canal. To confirm the net flux of the canal, empirical data is needed for solving the relationship between nutrient concentrations and mixing dynamics. This study only provided a crude calculation of the outflux of different nutrients. Furthermore, closing the nutrient budget can be achieved with supplemental measurements of benthic respiration, allochthonous input, and sedimentation rate. Establishing a nutrient budget with consistent monitoring effort will help us understand the evolution of the canal as a micro-estuary. Overall, the Ala Wai canal has the potential to become a constructed wetland with greater service capability beyond simple drainage and sediment catchment.

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