Channel Islands Harbor: Nutrient Sources and Sinks Study

Presented to:

The City of Oxnard

Presented by:

Aquatic Bioassay & Consulting Laboratories, Inc., and

Aquatic EcoTechnologies, Inc.

March 2019

Contents

Executive Summary

Project Background: A massive algal bloom occurred in the water column of Channel Islands Harbor (CIH) in June 2018. The bloom was followed by a widespread depleted oxygen event presumably related to bacterial decomposition of dying algae and animals killed by the growing anoxia. The bloom and subsequent event appear to have been related to changes in circulation in CIH in response to the decommissioning of the cooling water pumps of the Mandalay Power Generating Station on March 29, 2018.

Undertakings and Findings: A hydrological study was conducted by Anchor, QEA after the pumps were decommissioned, using the EFDC model (Environmental Fluid Dynamic Code) at the direction of the Los Angeles Regional Water Quality Control Board. It concluded that the residence time of water in CIH has dramatically increased, resulting in the potential for excessive algal accumulation, and subsequent depletion of dissolved oxygen in the water when the bloom died and was decomposed. Given the present lengthy water residence times, the probability of additional incidents (algal blooms and low dissolved oxygen concentrations) is high.

The City, in conjunction with Aquatic Bioassay and Consulting, Inc. and Aquatic Ecotechnologies, initiated a multi-faceted program to document recovery, monitor and plan a strategy to address the situation. An automated sensor package was deployed in August 2018 to measure dissolved oxygen, and chlorophyll fluorescence (a proxy for algal biomass). Measurements to date have revealed variable algal biomass and dissolved oxygen in the northern region of CIH during summer 2018, with conditions slowly improving and stabilizing in late summer and fall. Four new instruments were deployed in March 2019 and will be instrumental in identifying emerging future water quality events.

The nutrient study is assessing: (1) What is the relative importance of the episodic input of nutrients from rain events compared to chronic inputs that take place during the extensive dry weather in the region? and, (2) What are the main point sources of nutrients entering CIH during dry weather and seasonal rains? The nutrient assessment, that was begun in July 2018 and continued through the fall, examines nutrient concentrations in the water column and sediments of CIH.

- Rain events, and the consequent runoff into CIH resulting from these events, constitute major episodic pulses of plant nutrients (phosphorus and nitrogen) to CIH, with high contributions to the northern area of CIH from Edison Canal and to a much lesser extent the southeastern region of the harbor.
- During dry weather periods nutrients were measured at much lower concentrations compared to after rain events.
- When compared to other locations around the world, CIH had nutrient concentrations like pristine or low impact habitats during dry weather, and mid to high impact habitats during wet weather.
- Water sampling to assess the algal community demonstrated the presence of potentially toxic species of algae in CIH in summer 2018. Monitoring of these species is ongoing.

- Sediment concentrations of nitrogen were elevated at Seabridge and Mandalay, where some of the lowest water concentrations of dissolved oxygen were measured during the June 2018 bloom event.
- The concentrations of plant nutrients (nitrogen and phosphorus) in the sediments of CIH are substantial. Concentrations in some areas (e.g. Edison Canal) are similar to concentrations that have been reported from nutrient-impacted coastal ecosystems. These nutrient-enriched sediments represent reservoirs of nutrients that could support large algal blooms if they are mobilized from the sediments into the overlying water.

Recommendations

Short-term recommendations

- Design and enact a water quality 'early warning' monitoring program focused on measuring dissolved oxygen concentrations, algal biomass (using chlorophyll as a proxy) and algal species composition throughout CIH. *This recommendation has been initiated using automated sensors and manual water sampling to monitor algal species composition.*
- Identify and communicate to the public 'problem areas' and 'problem times' within CIH where/when algal blooms and/or low concentrations of dissolved oxygen occur, using information being collected by the automated sensors. *This recommendation has been initiated*.
- Design, and be prepared to activate, a Response Plan that will allow rapid response to algal blooms or low dissolved oxygen events to minimize their impact. *Given the long water retention times of CIH and the level of nutrient loading, additional poor water quality events are likely.*
    - Plan for additional water sampling and monitoring should an event appear imminent. *This process is in place.*
    - Efficiently communicate these events to the Public. *This process is in place.*
    - Plan for immediate removal and disposal of dead or dying animal life (to prevent further decreases in dissolved oxygen). *This emergency response process is currently being developed by the City.*
    - Plan for a short-term, small-scale mitigation strategy to address emerging problems before they worsen or spread. *A pilot study to apply hydrogen peroxide to surface waters during an algal bloom to control the size and magnitude of the bloom is being proposed*.
- Continue the effort to identify the most significant sources of plant nutrients (nitrogen and phosphorus) entering CIH, and their loss from the harbor (sinks), to inform a long-term strategy for reducing nutrient inputs.
- Evaluate the effectiveness of mitigation approaches such as mechanical aeration of the harbor basins to increase and maintain dissolved oxygen concentrations in areas of CIH subject to low oxygen levels.

Long-term recommendations

- Maintain a long-term water quality and sediment monitoring program focused on measuring dissolved oxygen concentrations, algal biomass (using chlorophyll as a proxy), algal species composition, and nutrients throughout CIH.

- Consider implementation of nutrient source controls (e.g. agricultural runoff) to reduce nutrient loadings to CIH via the Edison Canal. Since the City of Oxnard does not own the Edison Canal, this approach will require the inclusion of Stakeholders from agriculture, regulatory and municipal agencies, and the public. Solutions might include:
    - Source reductions into the Edison Canal: fertilizer application reduction; crop rotation, relocation, and change; and reduction in the amount of agricultural land uses
    - Engineered runoff reduction and treatment: bioswales, treatment wetlands, wetlands restoration, and engineered treatment systems
    - Decommissioning of the Edison Canal by blocking the flow of water into CIH; dredging the canal; or capping the canal with sediments. Each of these solutions are obviously the most cost prohibitive and must be balanced with societal needs.
- Continue to identify specific locations in the CIH where nutrient inputs are greatest and where control measures will provide the greatest benefit. This approach would include linking the hydrological model with old and emerging water and sediment nutrient data to define the pathways and rates of movement of nutrients into and out of CIH. This work will help identify the rates of nutrient uptake, burial and recycling in CIH. Use this model to inform the design of a nutrient management strategy to reduce nutrients entering the water column of CIH. This model could help identify:
    - If potential improvements in water quality derived from dredging sediments from the back basins would outweigh the increasing water retention times because of increased basin depth and possible reductions in water quality.
    - The specific locations of storm drains entering the CIH that consistently carry the greatest loads of nutrients. These drains would be identified for remediation efforts.

Background and Pre-existing Conditions in Channel Islands Harbor

The Channel Islands Harbor (CIH), City of Oxnard, CA is an artificial harbor established in the 1960s and '70s by dredging initially carried out by the Army Corps of Engineers. The present configuration is an inland water development encompassing an extensive small craft harbor, residential and commercial areas. The main connection to the coastal ocean is located at the southern terminus of the harbor (aerial photo on left of Figure 1). Tidal mixing exchanges water between the ocean and CIH. In the past, a canal (Edison Canal) connected the northwestern corner of the harbor near Westport to the ocean, with the opening to the ocean located approximately 3 km to the northwest of CIH. Until March of 2018, water was drawn from the Canal (and consequently from the northern end of CIH) by the Mandalay Power Generating Station for use in its once-through cooling system. The water was then discharged into the coastal ocean.

Anecdotal information indicates that *water quality within CIH has been good historically*, although quantitative information is sparse. A modest water quality study conducted by NRG Energy at three locations within CIH during 2016 confirmed that inference (graphical data in Figure 1). Measurements of chlorophyll fluorescence (a proxy for total algal biomass in the water) made through the water column revealed very modest concentrations of algal biomass in the water column on three sampling dates during summer 2016 (purple lines in the graphs of Figure 1). Most values were less than 3 mg chlorophyll/m^3 (= 3 µg chlorophyll/L). These *values are indicative of low algal biomass in the water* of CIH. By way of comparison, algal blooms along the coast of southern California generally attain values of 10-40 µg chlorophyll/L [1, 2]. Measurements of dissolved oxygen (DO) during 2016 (dull green lines in the graphs in Figure 1) were relatively high (generally 6-8 mg/L) throughout the water column, indicating *well-oxygenated water for an inland water body along our coast*.

The activity of the Mandalay pumps (until their cessation in 2018) constituted a significant and constant draw on the seawater present in the bays and inlets of CIH. Their activity maintained modest residence times for water in the harbor overall (Figure 2, left). Low residence times indicate water moving through CIH swiftly, thereby limiting the time that algae can utilize nutrients present in the water column and increase in abundance. Water residence times in CIH were measured and modeled in 2001 by Moffatt and Nichol [3]. That study reported that residence times were greatest (i.e. water was most stagnant) at Seabridge (≈6 days) but *water residence times were generally <5 days at all other locations within the harbor. The low residence times present while the Mandalay pumps were operating are presumably (in part) the reason for the low algal biomass and good water quality that has been observed within CIH* (e.g. in the report by NRG Energy, 2016).

Poor Water Quality Event during Summer 2018, and Initial Ecosystem Recovery

The pumps that provided once through cooling (OTC) water to the Mandalay Power Generating Station were decommissioned on March 29, 2018, as part of a California State Water Resources Control Board mandate, ceasing the draw of water from CIH. A hydrological study, similar to the one conducted by Moffatt & Nichol Engineers in 2001, was conducted by Anchor QEA in 2018 after the pumps were turned off to reassess water residence times in various regions of CIH. At the direction of the Los Angeles Regional Water Quality Control Board, the EFDC model (Environmental Fluid Dynamic Code) was used. The findings were dramatically different with the pumps no longer functioning (Figure 2, right). *Water residence times* with the pumps off now range from *15-17 days* in the southern harbor, and up to *53-70 days* at the upper end of the Edison Canal. The *water residence times within CIH proper are >21-24* along the easternmost and westernmost bays and inlets, and 23-30 between Seabridge and Westport at the northern end of the harbor. *These indicate water was remaining stagnant in CIH for 4-5 times longer compared to when the Mandalay pumps were operating*.

The concern with these findings is the much longer period of time that algae in the water have to grow and multiply, and the longer period allowed for bacterial decomposition once an algal bloom dies. Increased residence times were presumably a major factor contributing to a massive algal bloom and subsequent anoxic event that occurred during June 2018. *The upper reaches of CIH (particularly Westport and Seabridge areas) experienced a massive algal bloom during June 2018*, followed by *intense and prolonged low dissolved oxygen concentrations* lasting into July, likely a consequence of bacterial degradation of the dying algal bloom.

The City initiated water quality sampling throughout the Harbor in response to the event. Measurements were taken in near-surface waters at 30 locations to measure dissolved oxygen (and other parameters) beginning June 23, 2018 (Figure 3). Several locations in the northern region of CIH near Westport and Seabridge still *exhibited dissolved oxygen concentrations at or near 0 mg/L* (red color in contour plots from June 23 and 24; upper panels in Figure 3) on June 23 and 24, more than a week after the algal bloom was reported. Dead marine animals (fish) were observed at some locations in the northern harbor. Dissolved oxygen concentrations were higher but still impacted (i.e. low; <4 mg/L) near W. Channel Islands Blvd. on June 23 and 24.

Dissolved oxygen measurements in near-surface waters were repeated on June 26 and 28. *Values were found to be substantially higher overall* (lower panels in Figure 3), *indicating a marked improvement in water quality at that time.* Water in the Westport and Seabridge areas was still impacted (≈4 mg/L) but water south of those locations was highly oxygenated (blue color in contour plots from June 26 and 28; lower panels in Figure 3.

Additional studies were initiated in July 2018 to reexamine dissolved oxygen concentrations within CIH, and to begin to expand the breadth of the study to include a nutrient assessment and characterization of the phytoplankton community.

Dissolved oxygen concentrations were measured throughout the harbor on July 6, 2018 (Figure 4) by Aquatic Bioassay & Consulting Laboratories. *All areas showed a dramatic recovery* from the poor water quality event experienced in the early summer. Highly oxygenated waters were present near the water surface at all locations sampled (left panel in Figure 4), and in near-bottom waters throughout most of the harbor (right panel in Figure 4). Slightly lower concentrations of dissolved oxygen (but still adequately oxygenated) were observed in near-bottom waters along the periphery of the upper harbor (greenish color in the right panel of Figure 4.

Water samples were also collected on July 6, 2018 and analyzed for extracted chlorophyll *a* concentrations, algal abundances and species composition, and major nutrients (Figures 5, 6). Chlorophyll *a* concentration provides a proxy for total algal biomass in the water sample. *Chlorophyll values indicated the presence of a moderate algal bloom in the Seabridge and Westport areas of CIH during early July*, with values >10 µg/L (red color in left panel in Figure 5; note previously mentioned citation indicating that 10-40 µg /L represents a threshold for a regional coastal blooms). Microscopical analysis of the water samples provided measurements of total algal abundances and major taxonomic groups in the water. Microscopy revealed moderately high total abundances of algae in the water in the northern area of CIH (red color in right panel, Figure 5), and that *the community was dominated by a potentially toxic alga,* Pseudo-nitzschia.

Major inorganic forms of nitrogen (ammonium, nitrate) and phosphorus (orthophosphate) measured in water samples collected on July 6 (Figure 6) provide an indication of the potential for further algal growth. *All constituents exhibited concentrations that were moderate*, representative of coastal embayments within the region. That is, nutrient concentrations were not excessively high at that time.

Establishing a Monitoring Program and a Nutrient Assessment of CIH

An autonomous sensor package was installed at station 24 in early August (see Figure A2 for location) between Seabridge and Westport (the site of the algal bloom and subsequent low dissolved oxygen event in June 2018). The instrumentation continuously monitored several parameters including dissolved oxygen and chlorophyll fluorescence from August through November 2018, providing a continuous record of the degree of water column oxygenation and total algal biomass. *Dissolved oxygen measured by the instrument package indicated a relatively well-oxygenated water column for most of the surveillance period* (upper panel, Figure 7). Values remained above 4 mg/L for the entire sampling period with two exceptions. *Very low, albeit brief, decreases in dissolved oxygen (to ≈0 mg/L) were recorded in mid-August and late-September*. Values returned to well-oxygenated conditions within a few days in both instances. Dissolved oxygen then remained consistently high (>6 mg/L) from mid-October until November, indicating more stability of the water chemistry at a level of adequate oxygenation during fall 2018.

The generally high values for dissolved oxygen observed indicated *significant recovery of the ecosystem* during August and September, but the occasional decreases that were observed implied that the system was still vulnerable to low oxygen events. *The two transient low oxygen events could easily have resulted in another major anoxic event.* Large, rapid daily shifts in dissolved oxygen concentration were observed in King Harbor of the City of Redondo Beach in 2011 preceding a massive fish kill in that harbor by several days [4]. *It is noteworthy that the large but short-lived fluctuations of dissolved oxygen observed in CIH in August and September 2018 would most probably have been missed by sampling conducted by hand.* The continuously recording instruments provided *unmatched temporal coverage* that enabled characterization of important deviations in water chemistry and *serves as an early warning system for potential algal blooms*.

Measurements of chlorophyll fluorescence made using the sensor package revealed *high algal biomass and an ongoing algal bloom during August* (lower panel, Figure 7). Algal biomass decreased during September and was *consistently low from mid-October through November* (although two brief increases occurred in September and October). These findings are in agreement with the dissolved oxygen measurements indicating a highly variable situation at the sampling site for much of the summer, with a high degree of oxygenation and lower algal biomass becoming more consistent through the fall.

During the period of deployment of the autonomous sensors (August-November), weekly water samples were collected at the site of the sensor package (station 24) and at two additional stations within CIH (station 6, 23) for analysis of extracted chlorophyll values (to correlate with continuous chlorophyll fluorescence measurements made by the autonomous sensor package), and to obtain abundances of algae and species composition of the algal community. *Extracted chlorophyll measurements* made on discrete samples collected at three stations (Figure 8) *indicated similar overall trends* as the sensed chlorophyll fluorescence values obtained using the autonomous sensor package at station 24, although with much less temporal resolution than was obtained with the automated instrumentation (lower panel, Figure 7). Values were variable during August and into September, with some values indicating near-bloom conditions, but all values were consistently low moving into October and November. Note that chlorophyll fluorescence values obtained using the autonomous sensor package are typically much higher than extracted chlorophyll values, a finding that is not surprising given the different methods of analysis.

Abundances of microscopic algae (upper panel, Figure 9) were in agreement with total algal biomass determined from extracted chlorophyll (Figure 8). That is, *algal abundances were variable but generally high during the first half of the observation period*, but abundances *were generally low during most of October and into November*. The potentially toxic alga, *Pseudo-nitzschia* was the dominant alga present during August at all three sampling sites, but this alga was undetected or near the limit of detection during September-November. *High abundances of Pseudo-nitzschia within CIH was unexpected and should receive scrutiny in the future*.

Three extensive sampling surveys were conducted to assess nutrient concentrations within CIH and the adjoining Edison Canal. One survey (performed Oct 8-9, 2018) was conducted during a prolonged dry-weather period. Two additional surveys (Nov 22 and Nov 29, 2018) were conducted immediately following significant rain events (>0.5 in) to assess the importance of transient rain on nutrient delivery into CIH. *Assessing the concentrations of nutrients that support algal growth during contrasting seasonal/meteorological conditions provides vital information on major algal nutrient sources and therefore the potential to promote algal blooms in CIH.*

Results from the three nutrient surveys were dramatically different, particularly between the dry and post-rain sampling surveys (Figures 10, 11). Constituents measured included nutrient nitrogen (ammonium and nitrate) and total nitrogen, nutrient phosphorus (orthophosphate) and total phosphorus. 'Total' nitrogen and phosphorus include those elements present in inorganic (nutrient) form as well as these elements present in living and non-living particulate material and dissolved organic substances in the water. The proportions in which these elements exist (dissolved inorganic and organic form, living organisms, non-living particles), and the ratio between nitrogen and phosphorus, provide an indication of the primary factors driving algal growth and species composition in the water.

Values for all nitrogen and phosphorus constituents were substantially higher in the water column of CIH when sampled immediately following a rain event relative to sampling during dry weather (prevalence of warmer colors in Figures 10 or 11; compare the column of panels on the left of each figure [dry sampling event] to the columns of panels in the middle [1st rain event] and on the right [2nd rain event]). Higher nutrient concentrations in the water following a rain event was an anticipated result, as nutrients contained in runoff water might be expected to contribute significantly to standing stocks of nutrients present in the water. However, *the magnitudes of some of the values were remarkable, as was their localization within CIH*.

Ammonium concentrations were generally low in CIH during the dry weather sampling event (note large cool colors in the contour plot, top left panel in Figure 10), but increased substantially immediately after rain events (note warm colors in top middle and top right panels in Figure 10). *These values indicate large amounts of ammonium (a plant nutrient) entering CIH throughout the harbor and Canal during rain events.* Ammonium in CIH was higher than in the Edison Canal following the first rain event, but was higher in the Canal following the second rain event. Ammonium constituted a higher portion of inorganic nitrogen (relative to nitrate, another plant nutrient) in CIH following rain events, while nitrate generally constituted the larger portion of inorganic nitrogen (relative to ammonium) in the water column of Edison Canal after rain events (compare top row of panels in Figure 10 with the middle row of panels). Several nitrate values were off-scale of the color contour scale used in Figure 10 and are shown on the Figure as numerical values. *These values are quite high, generally 2-6 times higher than nutrient rich deep water in our coastal ocean. They indicate that rain events are an important source of nitrate to CIH. If fully utilized by algae in the water column, they present the potential to support a massive phytoplankton bloom.*

Total nitrogen values (bottom row of panels in Figure 10) revealed that much of the nitrogen present in the water column during the dry sampling event was present in living and non-living particulate material and/or dissolved organic nitrogen. Additionally, values following both rain events were several-fold higher than values measured during the dry season, particularly in the southeastern portion of CIH and in Edison Canal. *These findings implicate runoff following rain as important sources of nitrogen entering CIH*.

Measurements of inorganic nutrient phosphorus (orthophosphate) and total phosphorus in the water column of CIH mirrored the basic pattern observed for nitrogen. That is, concentrations of orthophosphate were very low at the time of the dry weather sampling (top left panel in Figure 11), indicating that the algal growth had consumed most of the available nutrient in the water column at that time. *Concentrations of orthophosphate following the rain events were dramatically higher*, especially following the first rain event (top middle panel in Figure 11). Also similar to nitrogen, total phosphorus measurements (orthophosphate, living and non-living particulate phosphorus, and dissolved organic phosphorus) were substantially higher than orthophosphate alone, and much higher following rain. Therefore, *runoff also constitutes a substantial source of phosphorus to CIH.* Particularly high orthophosphate concentrations were observed in the lower portion of CIH and in Edison Canal following the first rain event, indicating potentially different sources of orthophosphate entering CIH during and following rain events. Combined with the information on nitrogen, these results indicate that *rain events contribute substantial inputs of both elements to CIH* relative to their concentrations normally present in the water column of CIH and *implicates those events for a source of nutrient input into the harbor*.

The range of nitrogen and phosphorus values observed in the water column of CIH, and values observed in other coastal ecosystems are presented in Table 1. Values for CIH are outlined in red at the top of the Table, separated by sampling event (one dry weather and two rain sampling events). Values for other ecosystems are provided below the CIH data for comparison and have been arranged roughly in order from relatively ‘pristine’ ecosystems (containing very low concentrations of nitrogen and phosphorus) to ‘highly impacted’ ecosystems (containing very high concentrations) to provide context for the CIH data. Characterization as pristine, impacted, and so forth is approximate and only to provide context. Note that most ranges are large, indicative of seasonally changing conditions in all ecosystems. *Nitrogen and phosphorus values measured during dry weather conditions generally fell in a range observed for pristine or slightly impacted ecosystems.* An exception was Edison Canal where all constituents were present at concentrations more indicative of impacted ecosystems. In contrast, *many of the values measured following the rain events were commensurate with values that have been observed for impacted or heavily impacted ecosystems*, with Edison Canal yielding particularly high concentrations. While significant input of nutrients during rain events is to be expected, the results in Table 1 confirm that rain and runoff constitute major inputs of nitrogen and phosphorus to CIH.

A specific stoichiometric ratio between carbon, nitrogen and phosphorus atoms is generally observed in living organisms of marine plankton communities (106:16:1). This ratio is a common oceanographic metric referred to as the Redfield Ratio [5]. The ratio between nitrogen and phosphorus atoms (N:P = 16:1) is often used to establish which of these two elements (if either) limits the growth of the algal community. A ratio of 16:1 represents an ideal balance between nitrogen and phosphorus in most living things. Ratios lower than 16:1 indicate possible nitrogen limitation of algal growth (i.e. less availability of nitrogen, relative to availability of phosphorus), while ratios greater than 16:1 indicate possible limitation of algal growth by phosphorus. Severe phosphorus limitation has been implicated at ratios above ≈22:1 [6]. *Information on the N:P ratio of nutrients present in the water column thus provides insight into which element might be deficient, or alternatively, which element might be entering the water body in excess (through discharges, rain, runoff, etc.).*

Ratios of inorganic (nutrient) nitrogen (ammonium + nitrate) to inorganic (nutrient) phosphorus (orthophosphate) phosphorus observed throughout most of CIH during the three nutrient sampling events were highly variable (Figure 12). Ratios during the dry weather sampling period (top panel in Figure 12) revealed extremely high N:P ratios (172:1 and 303:1) in Edison Canal, indicative that *nutrient nitrogen was far in excess of nutrient phosphorus in the Canal.* Areas of CIH, particularly the northern and western regions of the harbor, also had high N:P ratios (>30) during the dry weather sampling. Regions in the central CIH, however, had much lower N:P ratios at that time, indicative of possible nitrogen limitation in those areas. N:P ratios during the two sampling periods following rain events were dramatically different in Edison Canal (bottom two panels in Figure 12). Overall, N:P ratios of algal nutrients in the water were in much closer agreement with the Redfield Ratio, or slightly above the optimal ratio of 16:1 after rain events. *Given that rain events contributed substantially to nutrient loading in CIH, and that the nutrient ratio was close to the Redfield Ratio, rain events appear to provide nutrient conditions very conducive to algal blooms.*

The range of N:P ratios observed in the water column of CIH, and values observed in other coastal ecosystems are presented in Table 2. The range of N:P ratios observed for CIH is remarkably large. The smallest ratios observed during dry weather conditions were at or below values observed in most other ecosystems listed in the Table, while the largest values (especially those observed in Edison Canal) are greater than all maximal values observed in the other ecosystems listed in the Table. *These results indicate the potential for different elements to control algal growth in different areas of CIH (or at different times in a single location) and reveals heterogeneity across the harbor and Canal that requires characterization of the various sources and sinks of limiting (or excess) nutrients across the ecosystem.*

Sediment samples were collected from CIH and Edison Canal on December 11 and 19, 2019, and analyzed for their total nitrogen and total phosphorus content (Figure 13). Sediments are typically repositories for large amounts of nutrient elements, particularly in hydrologically quiescent environments. These nutrients can become available for algal growth by release from the sediments to the overlying water. *Assessing the amounts of these elements in sediments provides an indication of the overall internal nutrient loading within the ecosystem. The sediment nitrogen and phosphorus measurements made in CIH will serve as baseline information for future measurements of sediment nitrogen and phosphorus that will indicate how the changed circulation in CIH and the Canal with the Mandalay pumps turned off will affect accumulation of these elements in the ecosystem*.

Total nitrogen values in the sediments of CIH and Edison Canal were highest in the northeastern and western regions of CIH where the algal bloom and subsequent anoxic event in 2018 was most pronounced (top panel, Figure 13). Lowest sediment nitrogen values were observed in the central CIH and in Edison Canal. Interestingly, total phosphorus in the sediments displayed somewhat the opposite spatial distribution as nitrogen, with lowest total phosphorus values in the northeastern and western regions of CIH (bottom panel, Figure 13). The reason for this disparity between sediment nitrogen and phosphorus is unknown, but may be related to: differences in depositional rates of the two elements in different regions of the harbor and Canal; difference in where or how fast denitrification (a process that transform inorganic nitrogen into a form that is unusable by algae) is removing nitrogen from the sediments; or of the differences in the immobilization of phosphorus or nitrogen in the sediments.

Ratios of total nitrogen to total phosphorus (TN:TP) in the sediments of CIH and Edison Canal were calculated from the values of those constituents. TN:TP ratios in sediments were very different than those ratios in the water column observed during sampling conducted during dry weather and following the two rain events (Figure 14). TN:TP ratios in the sediments were consistently low across CIH and Edison Canal (top right panel in Figure 14), compared to TN:TP ratios in the water column (top left and lower panels in Figure 14). Sediment TN:TP values were far below the Redfield Ratio of 16:1 (note cool color contours in the Figure). *These results imply either a loss of nitrogen from the sediments relative to phosphorus (perhaps a consequence of denitrification) or more effective immobilization of phosphorus in the sediments relative to nitrogen (or both) in this coastal ecosystem. The specific cause of the sediment N:P imbalance may play a role in affecting algal blooms and algal species composition if and when those nutrients are released from the sediments.*

A comparison of sediment nitrogen and phosphorus content to these elements in sediments of other coastal ecosystems revealed that *loading of nitrogen and phosphorus in CIH and Edison Canal has been substantial*, relative to other ecosystems where such measurements have been made (Table 3). Values in some localities of CIH and Edison Canal are representative of 'impacted' ecosystems. TN:TP ratios were similar to values reported from one study in Shark Bay, western Australia, but published data on these values are limited.

Glossary of Terms

Algae (for purposes of this report): Microscopic single-celled organisms in the water. They require dissolved inorganic (nutrient) nitrogen and phosphorus (among other elements) in order to grow photosynthetically.

Algal bloom: A substantial accumulation of algae in the water. Algal blooms can be 'harmful' (have negative effects) through the production of toxins (e.g. *Pseudonitzschia* spp. produces the neurotoxin domoic acid), or cause low dissolved oxygen when bacteria consume O_2 to degrade dead algae at the end of the bloom. The degradation of dead algae can also lead to foul odors.

Ammonium (NH_4^+): A dissolved, inorganic (non-living) form of nitrogen that is a source of nutrient for algae. Fish and aquatic invertebrates excrete ammonium as body waste. Some algae prefer to grow using ammonium rather than nitrate (another form of inorganic nitrogen) so they will preferentially absorb ammonium. Ammonium concentrations (in µM) are typically lower than nitrate.

Autonomous sensor package: An instrument composed of sensors for measuring various parameters in the water. The package deployed in this study included sensors for measuring temperature, conductivity (salinity), temperature, dissolved oxygen, and chlorophyll.

Chlorophyll: The light-absorbing green pigment in algae and plants. Quantifying it is often used as an approximation of the total amount of algal biomass present in the water.

Chlorophyll fluorescence: A measure of the amount of chlorophyll (plant pigment) in the water based on the release of red light (fluorescence) by the chlorophyll molecule when exposed to blue light. Chlorophyll fluorescence is often measured using a sensor deployed into the water.

Chlorophyll (extracted) concentration: A measure of the amount of chlorophyll (plant pigment) in the water based on a sample that was extracted with a solvent. Algae containing chlorophyll is first trapped on a filter paper and the chlorophyll is then extracted from the cells using acetone as a solvent. The amount of chlorophyll in the solvent is measured by quantifying the amount of red light (fluorescence) released by the chlorophyll molecule when exposed to blue light.

Denitrification: A biological process mediated by bacteria in which various inorganic forms of nitrogen [ammonium (NH_4^+), nitrate (NO_3^-), nitrite (NO_2^-), nitric oxide (NO) and nitrous oxide N_2O)] are converted to molecular nitrogen (N_2) and effectively removed from most biological processes as it is a form of nitrogen unusable by most algae.

Dissolved inorganic nutrients: Dissolved chemical compounds that support algal growth. The dissolved inorganic form of phosphorus is orthophosphate (PO_4^{-3}), while the dissolved inorganic forms of nitrogen include ammonium (NH_4^+), nitrate (NO_3^-), and nitrite (NO_2^-, usually at low concentration in water).

Dissolved oxygen (DO): The amount of gaseous oxygen (O_2) dissolved in the water. It can be affected by water temperature and algae producing O_2 through photosynthesis. A DO value of < 5 mg/L will be stressful to some aquatic life, and a value of < 2 mg/L may result in fish kills.

Micro-molar (µM): A concentration unit based on the actual number of atoms of an element or compound per liter of water.

Milli-gram per liter (mg/L): A concentration unit based on the weight of a compound per liter of water. Compounds having the same concentration in the unit of mg/L may have different actual numbers in a liter of water due to differences in the weight of an individual molecule. E.g. ammonium has a molecular weight of 18 g/mol while nitrate has a molecular weight of 62 g/mol, so for a concentration of 1 mg/L, there will be more ammonium molecules than nitrate molecules in 1 liter of water because nitrate is heavier. Such differences in molecular weight makes it inconvenient to compare concentrations in units of mg/L and thus µM is used in this report.

Nitrate (NO_3^-): A dissolved inorganic form of nitrogen that is a source of nutrient for algae. While some algae may prefer ammonium over nitrate, high concentrations of nitrate can still stimulate the formation of an algal bloom.

Nitrogen (N): An element that is a major nutritional requirement for algal growth.

Nitrogen-limitation: When the N:P ratio is <16 and algal growth is limited by nitrogen. An input of inorganic nitrogen may thus heavily stimulate algal growth.

Nitrogen:Phosphorus (N:P) ratio: The ratio of nitrogen atoms (or weight) to phosphorus atoms (or weight). Algal cells prefer to produce biomass within a strongly confined ratio of nitrogen atoms to phosphorus atoms (often referred to as the Redfield ratio). An imbalance in that ratio may limit algal growth (i.e. N-limitation or P-limitation), lead to changes in algal community composition, or even stimulate toxin production in certain algal species.

Orthophosphate (PO_4^{-3}): A dissolved inorganic form of phosphorus that is a source of nutrient for algae.

Phosphorus (P): An element that is a major nutritional requirement for algal growth.

Phosphorus-limitation: When the N:P ratio is >16 and algal growth is limited by phosphorus. An input of inorganic phosphorus may thus heavily stimulate algal growth.

Pseudo-nitzschia: A genus of a group of algae called diatoms. Some species within this genus produces the neurotoxin domoic acid. This toxin can accumulate up the food chain and lead to deaths of predators such as sea lions or even humans.

Redfield ratio (C:N:P=106:16:1): The general atomic ratio of carbon to nitrogen to phosphorus in organisms. Organisms thus require 16 nitrogen atoms for every 1 phosphorus atom. A value of >16 suggests phosphorus-limitation while a value of <16 suggests nitrogen-limitation.

Total nitrogen (TN): The total amount of nitrogen in a water sample, including dissolved nitrogen (e.g. ammonium and nitrate) and nitrogen that is bound up in cells or detritus.

Total phosphorus (TP): The total amount of phosphorus in a water sample, including dissolved phosphorus (i.e. orthophosphate) and phosphorus that is bound up in cells or detritus.

Water residence time: The length of time (days) a mass of water will remain in a certain area.

References

References in Report Text (references [1-6])
References in Table 1 (references [7-20])
References in Table 2 (references [11-13, 16])
References in Table 3 (references [21-33])

1. Kim, H.-J. et al. (2009) Coastal phytoplankton blooms in the Southern California Bight. Prog Oceanogr 82 (2), 137-147.

2. Seubert, E.L. et al. (2013) Seasonal and annual dynamics of harmful algae and algal toxins revealed through weekly monitoring at two coastal ocean sites off southern California, USA. Environ Sci Pollution Res 20, 6878-6895.

3. Nichol, E.M.A., Mandalay Bay tract 5266 development water quality model study, Report to Mandalay Partners, LLC, 2001, 31 pp.

4. Stauffer, B.A. et al. (2012) An oceanographic, meterological and biological 'perfect storm' yields a massive fish kill. Mar Ecol Prog Ser 468, 231-243.

5. Redfield, A.C. et al. (1963) The influence of organisms on the composition of sea water. In The sea (Hill, M.N. ed), pp. 26-77, Wiley.

6. Guildford, S.J. and Hecky, R.E. (2000) Total nitrogen, total phosphorus, and nutrient limitation in lakes and oceans: Is there a common relationship? Limnol Oceanogr 45 (6), 1213-1223.

7. Aguilera, P.A. et al. (2001) Application of the kohonen neural network in coastal water management: Methodological development for the assessment and prediction of water quality. Water Res 35 (17), 4053-4062.

8. Alonso-Rodríguez, R. et al. (2000) Trophic Conditions and Stoichiometric Nutrient Balance in Subtropical Waters Influenced by Municipal Sewage Effluents in Mazatlán Bay (SE Gulf of California). Mar Poll Bull 40 (4), 331-339.

9. Cloern, J.E. (2001) Our evolving conceptual model of the coastal eutrophication problem. Mar Ecol Prog Ser 210, 223-253.

10. Cociasu, A. et al. (1996) Long-term ecological changes in Romanian coastal waters of the Black Sea. Mar Poll Bull 32 (1), 32-38.

11. Correll, D.L. et al. (1992) Cross media inputs to eastern US watersheds and their significance to estuarine water quality. Water Sci Technol 25 (11), 2675-2683.

12. Harrison, P.J. et al. (1990) Phosphate limitation in estuarine and coastal waters of China. J Exp Mar Biol Ecol 140 (1-2), 79-87.

13. Hattenrath-Lehmann, T.K. et al. (2015) Nitrogenous Nutrients Promote the Growth and Toxicity of Dinophysis acuminata during Estuarine Bloom Events. PLOS ONE 10 (4), e0124148-e0124148.

14. Jarvie, H.P. et al. (1998) Nitrogen and phosphorus in east coast British rivers: Speciation, sources and biological significance. Sci Total Environ 210-211, 79-109.

15. Justić, D. et al. (1995) Stoichiometric nutrient balance and origin of coastal eutrophication. Mar Poll Bull 30 (1), 41-46.

16. Lie, A.A.Y. et al. (2011) Changes in the nutrient ratios and phytoplankton community after declines in nutrient concentrations in a semi-enclosed bay in Hong Kong. Mar Environ Res 71 (3), 178-188.

17. Lomoljo et al. (2009) Nitrate, ammonia and phosphate concentrations in the surface water of Kuala Gula bird sanctuary, west coast of Peninsular Malaysia. Pertanika Journal of Tropical Agricultural Science 32 (1), 1-5.

18. Nizzoli, D. et al. (2005) Impacts of mussel (Mytilus galloprovincialis) farming on oxygen consumption and nutrient recycling in a eutrophic coastal lagoon. Hydrobiologia 550 (1), 183-198.

19. Valiela, I. and Costa, J.E. (1988) Eutrophication of Buttermilk Bay, a cape cod coastal embayment: Concentrations of nutrients and watershed nutrient budgets. Environmental Management 12 (4), 539-553.

20. Wilkerson, F.P. et al. (2006) Phytoplankton blooms and nitrogen productivity in San Francisco Bay. Est Coasts 29 (3), 401-416.

21. Atkinson, M.J. (1987) Low phosphorus sediments in a hypersaline marine bay. Estuar Coast Shelf Sci 24 (3), 335-347.

22. Bader, R.G. (1954) Carbon and nitrogen in near shore marine sediments. University of Washington Department of Oceanography Technical Report 36.

23. Berghoff, S. et al. (2000) Phosphorus in sediments from coastal waters of Mecklenburg-Vorpommern (southern Baltic Sea). Proceedings in Marine Science 2 (C), 161-173.

24. Carroll, J. et al. (2008) Resource-restricted growth of eelgrass in New York estuaries: Light limitation, and alleviation of nutrient stress by hard clams. Mar Ecol Prog Ser 369 (June 2014), 51-62.

25. Farías, L. et al. (1996) Effect of Coastal Upwelling on Nitrogen Regeneration from Sediments and Ammonium Supply to the Water Column in Concepcion Bay, Chile. Estuar Coast Shelf Sci 43 (2), 137-155.

26. Filippelli, G.M. and Cowie, G.L. (2017) Carbon and phosphorus cycling in Arabian sea sediments across the oxygen minimum zone. Journal of Oceanography and Marine Research2 5 (4), 171-171.

27. Hamad, J.R.J. and Omran, A. (2016) Total organic carbon (TOC) and carbon/nitrogen ratio in surface sediments in Kuala Sungai Baru, Melaka. International Journal of Engineering 14 (2), 137-150.

28. Ladakis, M. et al. (2006) Nitrogen and phosphorus in coastal sediments covered by cyanobacteria mats. Journal of Soils and Sediments 6 (1), 46-54.

29. Marcomini, A. et al. (1995) Eutrophication of the Lagoon of Venice: Nutrient loads and Exchanges. (McComb, A.J. ed), pp. 59-80, CRC Press.

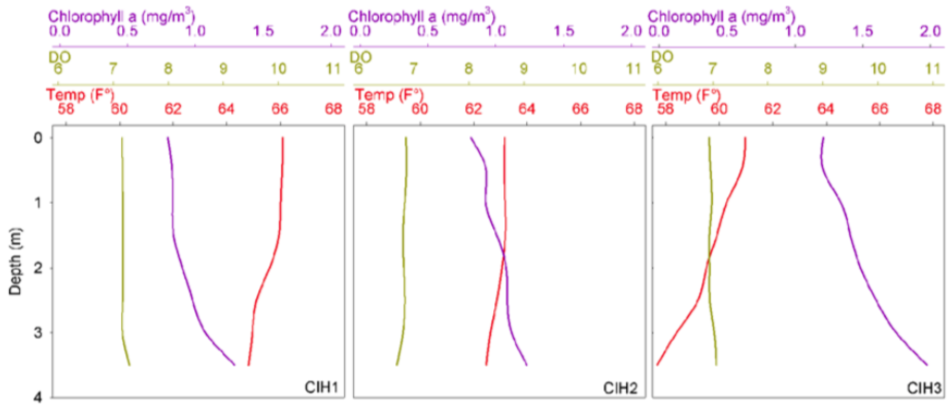
30. Müller, A. (1997) Hydrodynamics and nutrient distribution in bottom sediments of the Archipelago Sea, southwestern Finland. Boreal Environment Research 2 (3), 229-237.

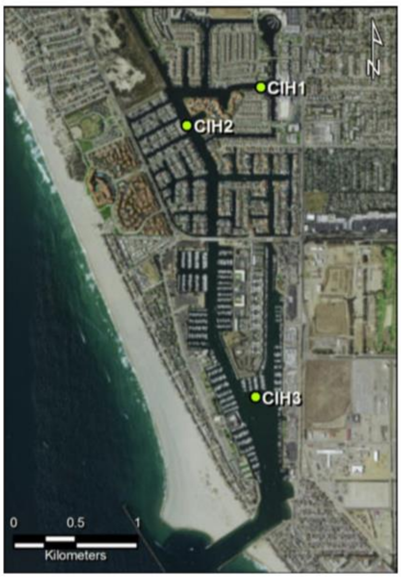
31. Puttonen, I., Phosphorus in the sediments of the northern Baltic Sea Archipelagos - Internal P loading and its impact on eutrophication, 2017.

32. Strom Richard, N. and Biggs, R.B. (1982) Phosphorus distribution in sediments of the Delaware River estuary. Estuaries 5 (2), 95-101.

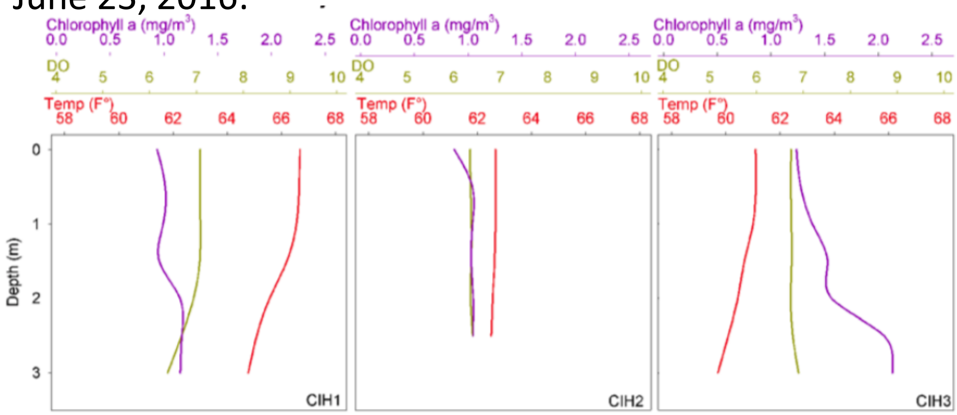
33. Thouvenot-Korppoo, M. et al. (2012) Phosphorus release and sediment geochemistry in a low-salinity water bay of the Gulf of Finland. Boreal Environment Research 17, 237-251.

June 9, 2016:





June 23, 2016:



July 13, 2016:

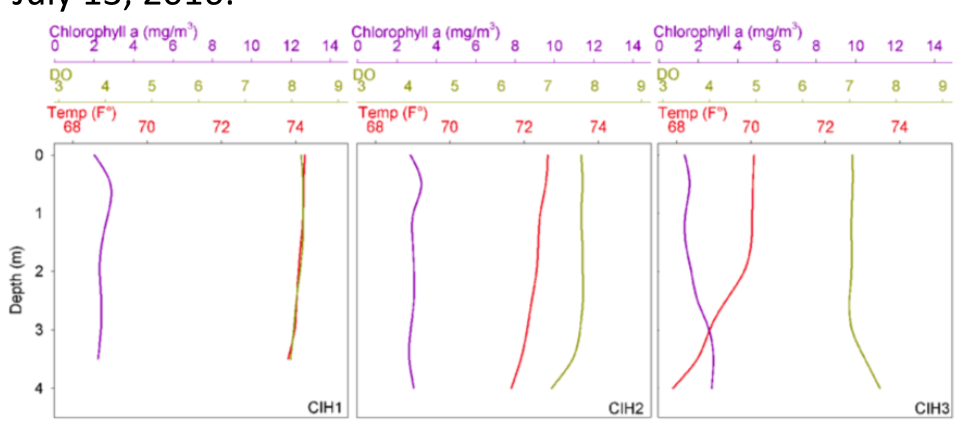


Figure 1. Vertical profiles of in-situ chlorophyll fluorescence (purple), dissolved oxygen concentrations (green) and water temperature (red), obtained at three locations in CIH during a water quality study conducted by NRG, June - July 2016. Station locations are indicated at the bottom right of each panel, and the locations of the sampling stations are shown on the map to the left. Water conditions during summer 2016 revealed a relatively unimpacted water column in CIH. Chlorophyll fluorescence was generally < 4 µg/L (= mg/m^3), indicative of non-bloom conditions, while dissolved oxygen concentrations were generally > 6 mg/L, also a relatively healthy condition.

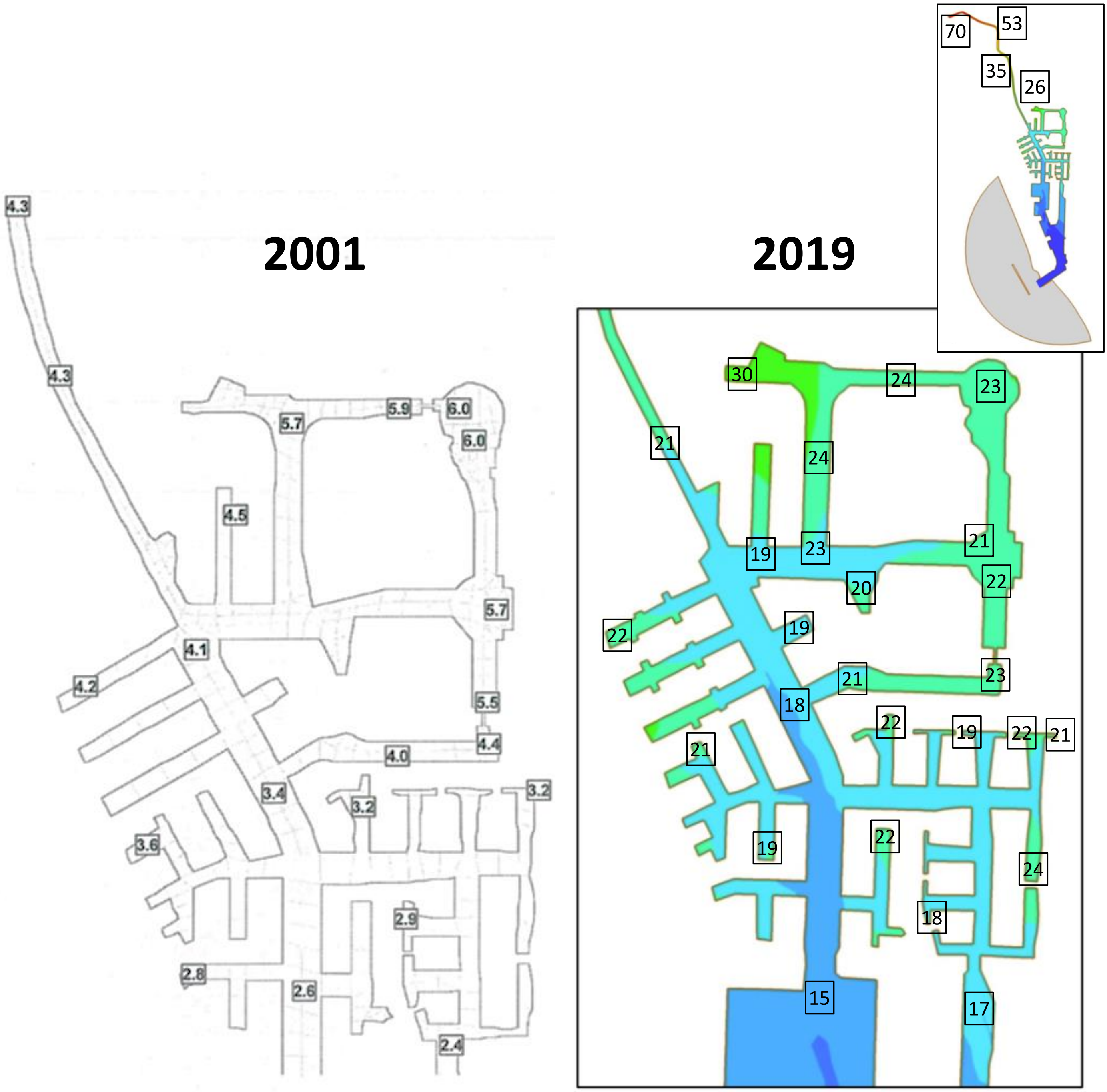


Figure 2. Modeled water residence times (approximately time that water remains in that location) in CIH based on conditions in 2001 with the Mandalay Power Plant pumps operating (left: from Moffatt & Nichol Engineers report, Fig. 3.7) and in 2019 with the Plant's pumps not operating (right: Anchor QEA memorandum, Fig. 7). The numbers indicate water residence times in units of days. Water residence times near Seabridge and Westport increased from approximately 6 days when the pumps were active (left) to 20-30 days with the pumps off (right), an increase of more than 3-fold. Water residence times in the upper portion of Edison Canal are extreme (≈70 days) with the pumps turned off (Shown in the small inset figure in the top right corner).

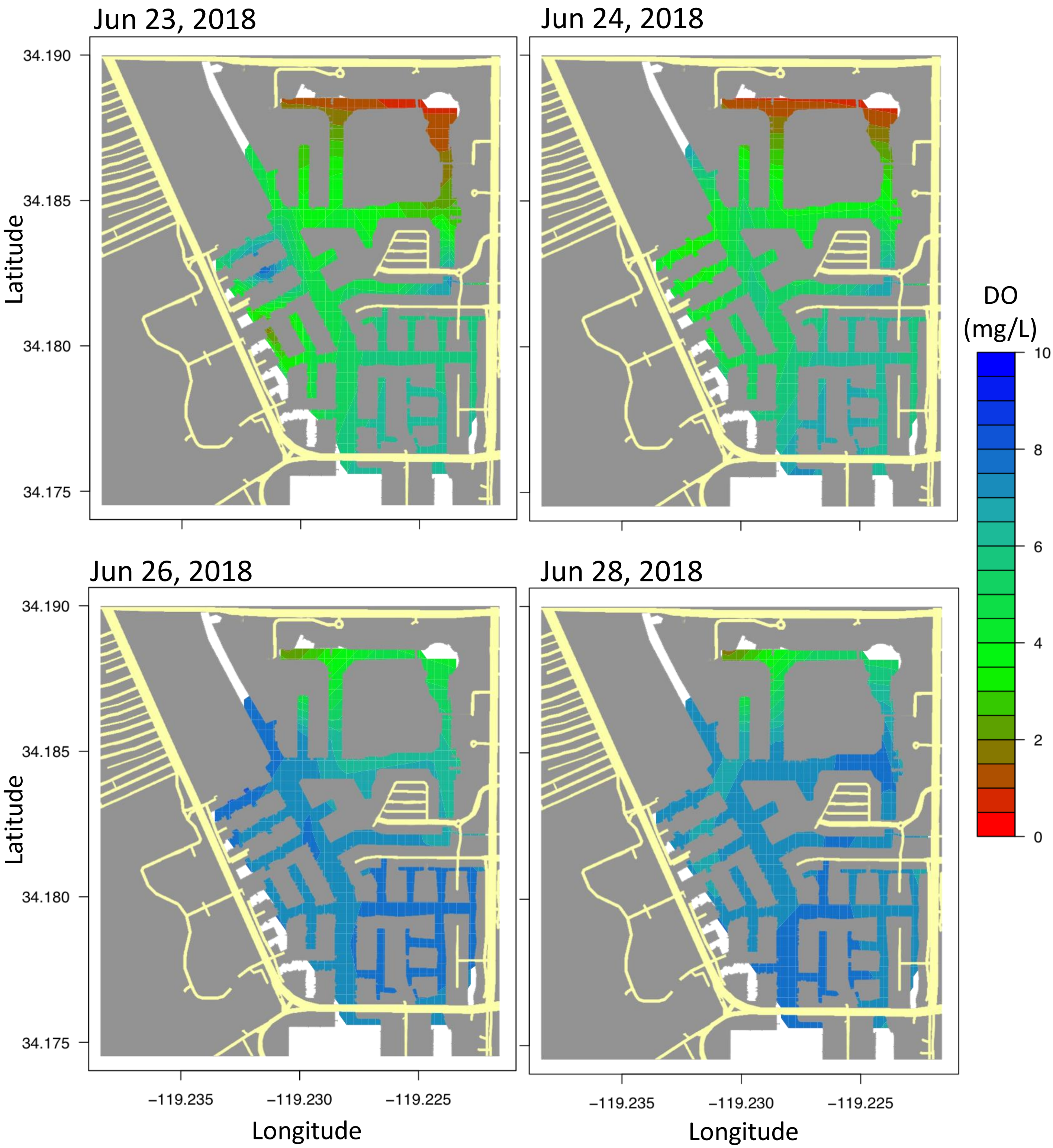


Figure 3. Color contour plots of dissolved oxygen (DO) concentrations near the water surface in CIH during late June and early July 2018. Reports of turbid and noxious odor from CIH began in mid June, City personnel took measurements throughout CIH beginning June 23. DO concentrations on June 23 and 24 (top panels) were very low (< 2 mg/L) in the northern region of CIH (Seabridge and Westport), and to a lesser extent (< 4 mg/L) in the western region of CIH. Partial recovery of DO occurred by the time of subsequent sampling on June 26 and 28 (lower panels).

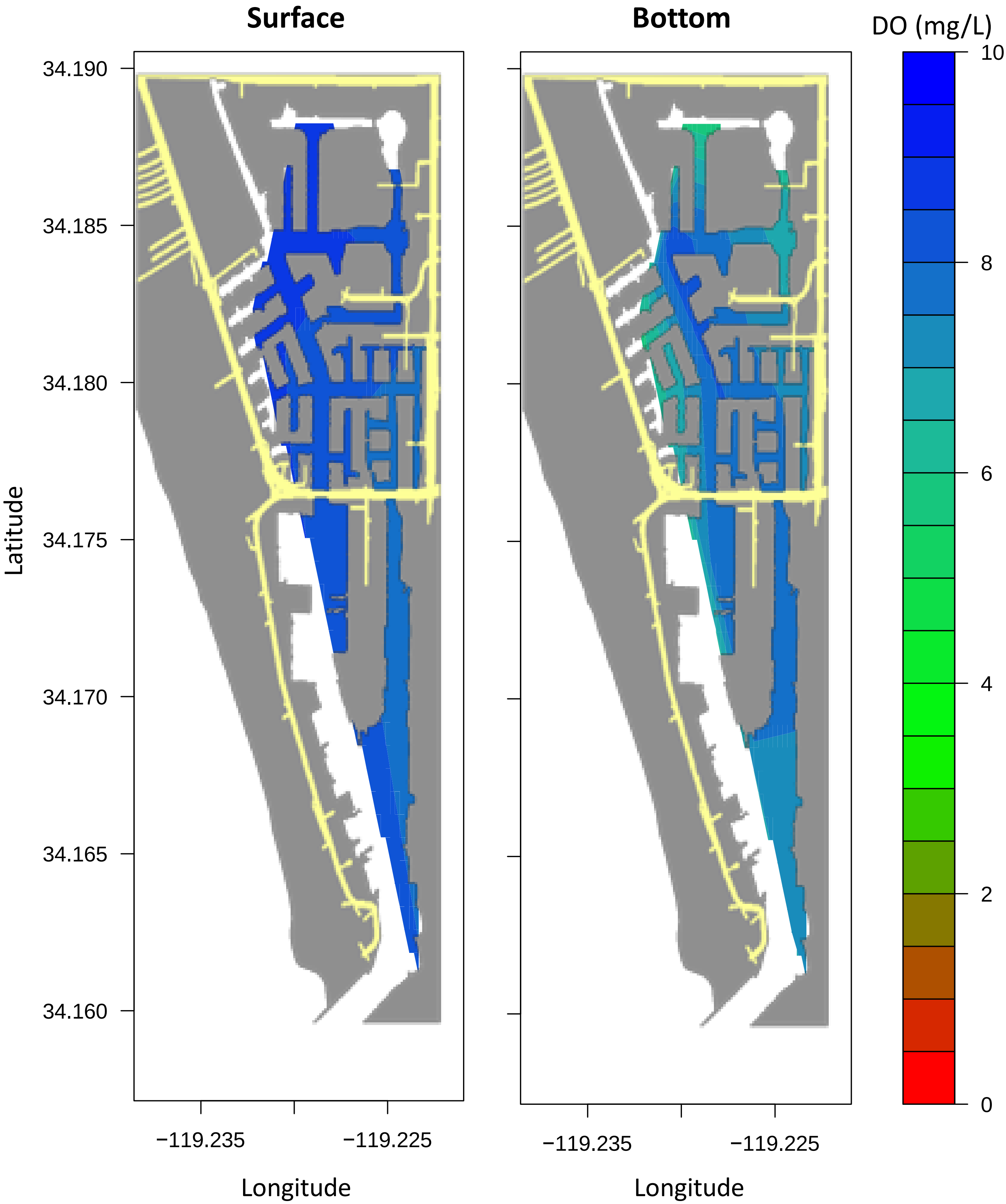


Figure 4. Color contour plots of near-surface (left) and near-bottom (right) dissolved oxygen (DO) concentrations in CIH on July 6, 2018 indicated a substantial recovery of DO to conditions of near-full oxygenation. Data for Seabridge Marketplace plaza were not collected because the boat could not access it during the sampling event.

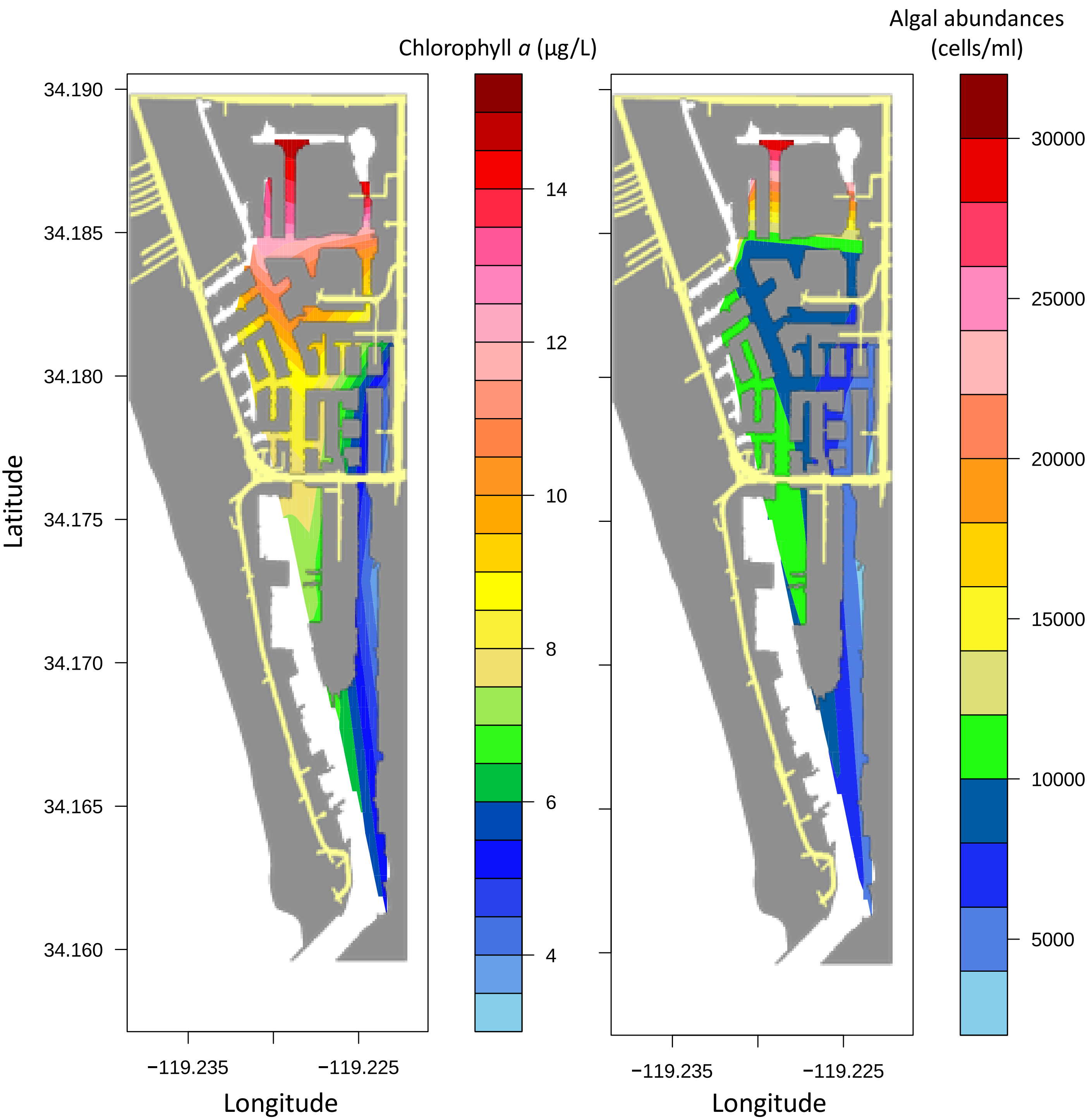


Figure 5. Color contour plots of extracted chlorophyll *a* concentrations (left) and algal abundances (right) throughout CIH on July 6, 2018. Chlorophyll values (a proxy for total algal biomass) were high (> 10 µg/L) in the northern region of CIH (left), but not indicative of a major bloom at that time. Similarly, algal abundances in the northern region of CIH were high in the northern region of CIH, with highest abundances (~ 33,000 cells/ml) around Westport (right). A majority of the cells were species of the potentially toxic diatom genus, *Pseudo-nitzschi*a. Data for Seabridge Marketplace plaza were not collected because the boat couldn't access it during the sampling event.

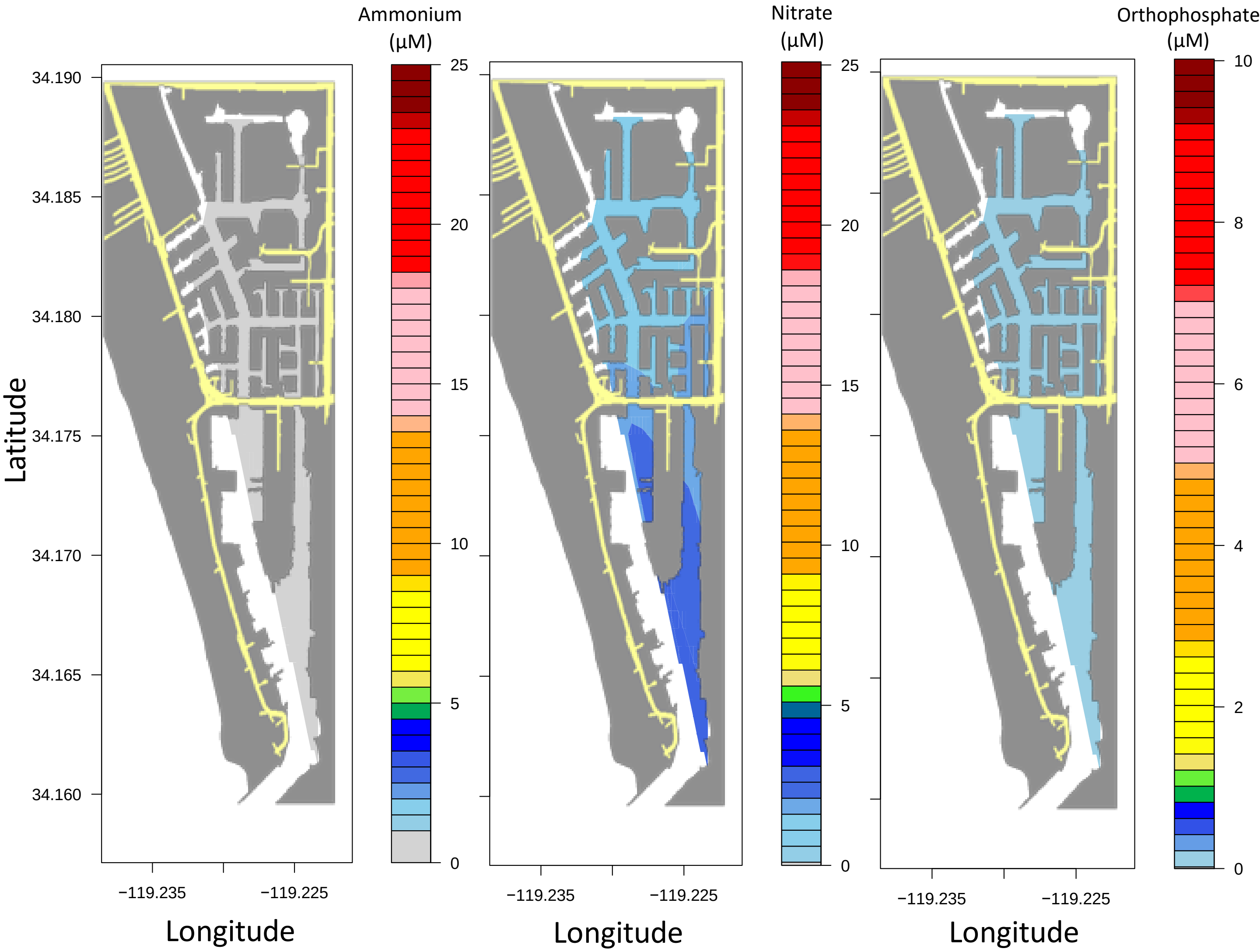


Figure 6. Color contour plots of concentrations of ammonium, nitrate, and orthophosphate in water samples collected in CIH on July 6, 2018. Nitrate was the dominant form of inorganic (nutrient) nitrogen in CIH on the sampling date. Both nitrate and orthophosphate (i.e. nutrient phosphorus) were measurable but not excessively high at the time of sampling (see Figs. 10, 11 for comparison, and Table 1 caption for discussion and interpretation). Data for Seabridge Marketplace plaza was not collected because the boat couldn’t access it during the sampling event.

Figure 7. Dissolved oxygen (DO) concentrations (top) and chlorophyll fluorescence values (bottom) obtained from a continuously recording autonomous sensor package deployed at station 24 (refer to Fig. A2 for station location) Aug 6 – Nov 20, 2018. Values indicated considerable recovery of the ecosystem by early August (DO 4-10 mg/L), but note two dates when DO concentrations plummeted to near-zero (mid-Aug, late-Sept). Both events were followed closely by short-lived (3-5 day) dramatic increases in chlorophyll fluorescence (indicative of increases in algal biomass). Overall, both parameters indicated a progressive improvement in water quality (i.e. towards higher DO and lower algal biomass; more stability in both parameters) late in the monitored period.

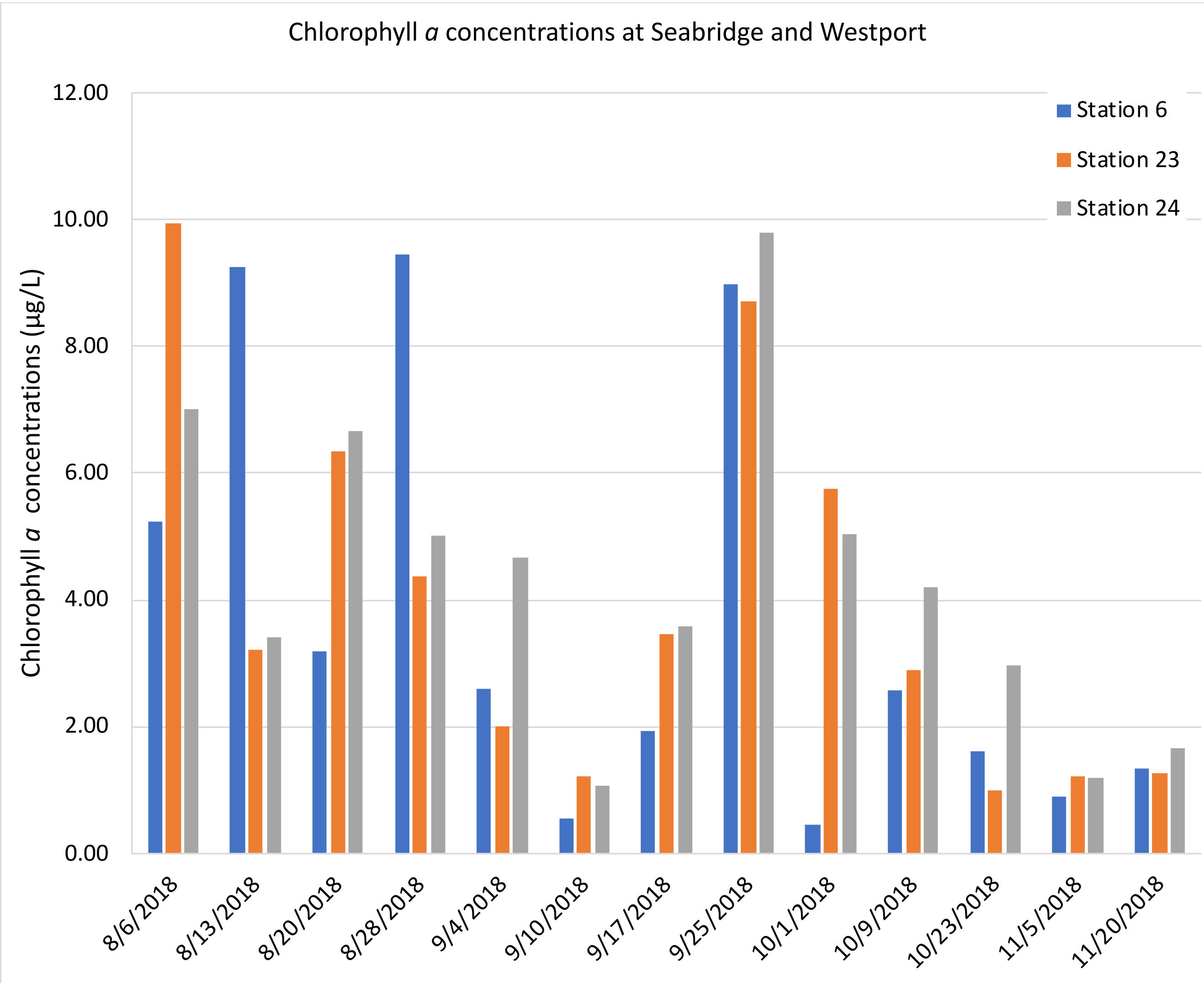
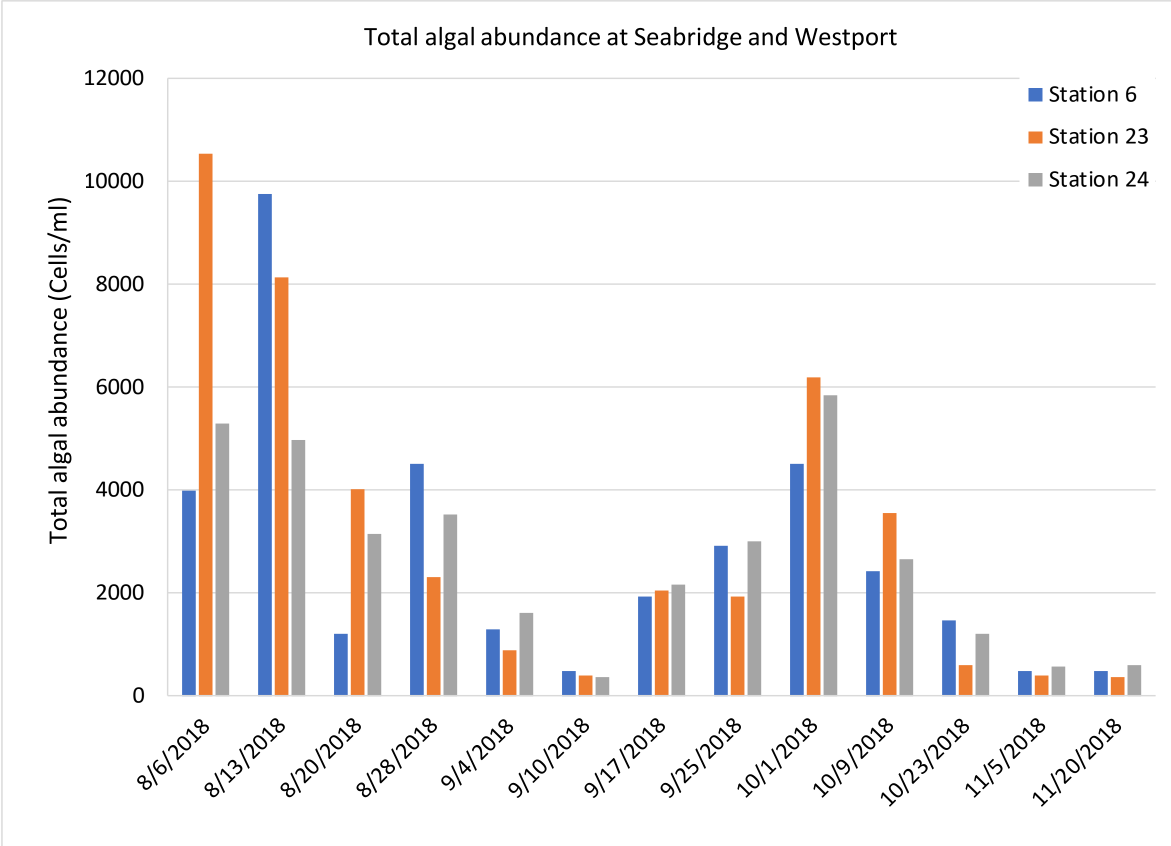


Figure 8. Extracted chlorophyll *a* concentrations (a proxy for total algal biomass) at stations 6, 23, and 24 (refer to Fig. A2 for stations location) from Aug 6 – Nov 20, 2018. All stations exhibited similar overall trends in chlorophyll *a* concentrations, and revealed decreasing algal biomass in CIH towards the end of the sampling period in 2018. Relatively high algal biomass (~10 µg/L) was observed during August and on September 25, when the in-situ sensed chlorophyll fluorescence values also showed spikes (shown in Fig. 7). (Note: absolute values of extracted chlorophyll and in-situ chlorophyll fluorescence from the autonomous sensor package are not expected to match).



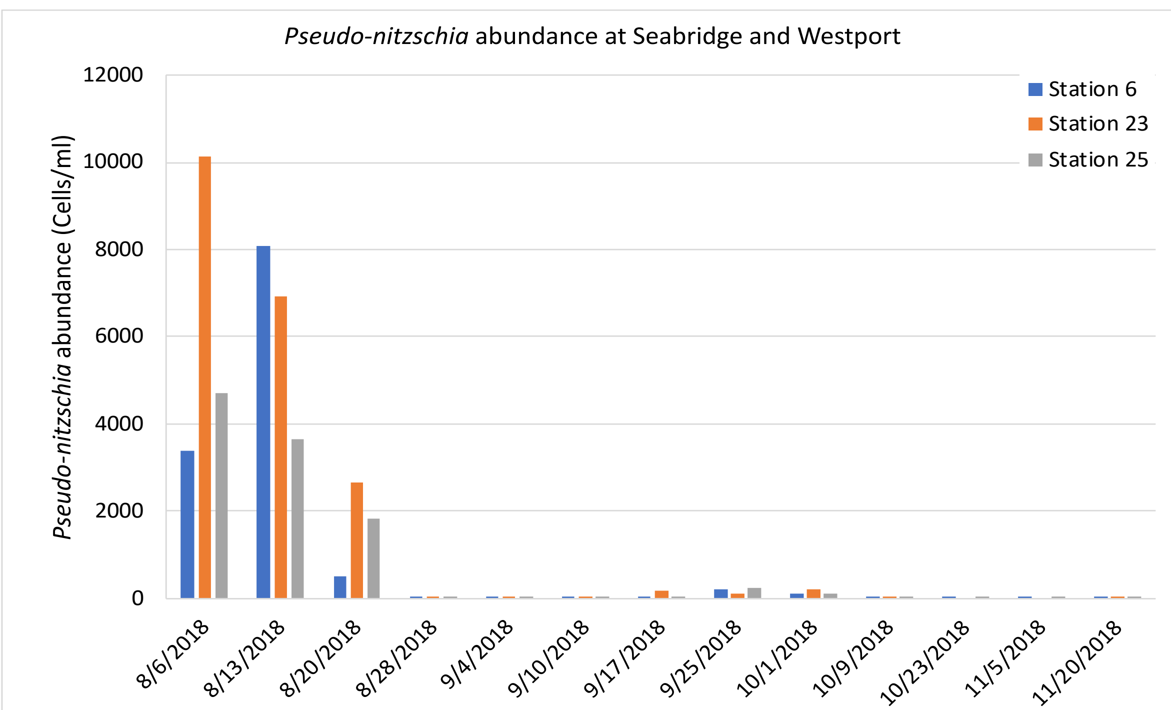


Figure 9. Total algal (top) and *Pseudo-nitzschia* spp. (bottom) abundances at stations 6, 23, and 24 (refer to Fig. A2 for stations location) from Aug 6 – Nov 20, 2018. Total algal abundances (top) exhibited a trend that was similar to changes in extracted chlorophyll *a* concentrations (Fig. 8), as expected. Potentially toxic diatoms (*Pseudo-nitzschia* spp.) were a major component of the algal community early – mid Aug (bottom), but decreased dramatically in late August.

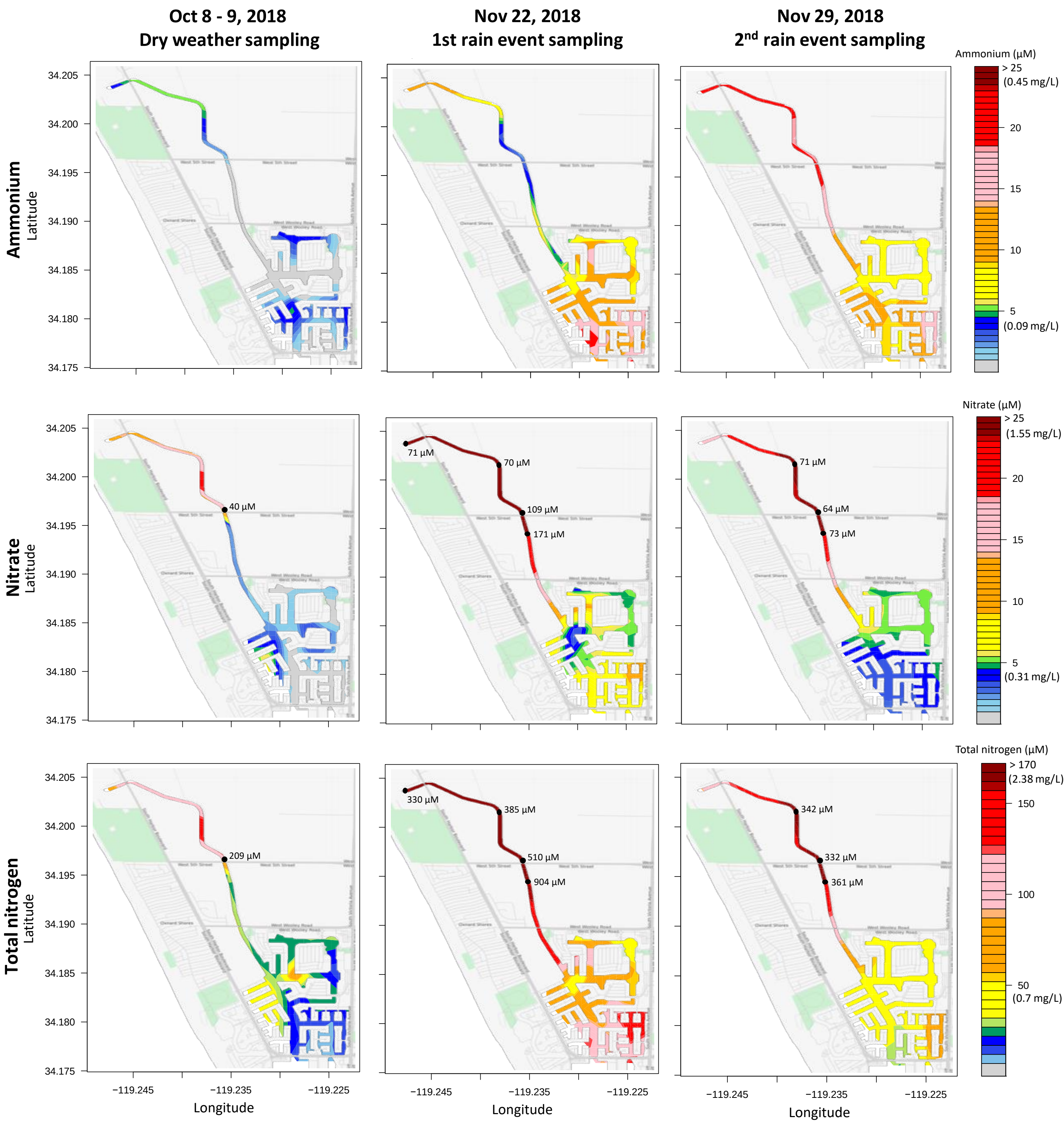


Figure 10. Color contour plots showing concentrations of ammonium (top row), nitrate (middle row), and total nitrogen (bottom row) in near-surface water during a dry weather sampling (left column) and two sampling dates following significant rain events (middle and left columns) in CIH and Edison Canal. Nutrient concentrations were substantially higher following rain events (relative to the dry weather sampling). Nitrate concentrations (middle row) were generally higher than ammonium concentrations (top row). Samples with values larger than the scale range are indicated by black dots along with the concentrations at those locations.

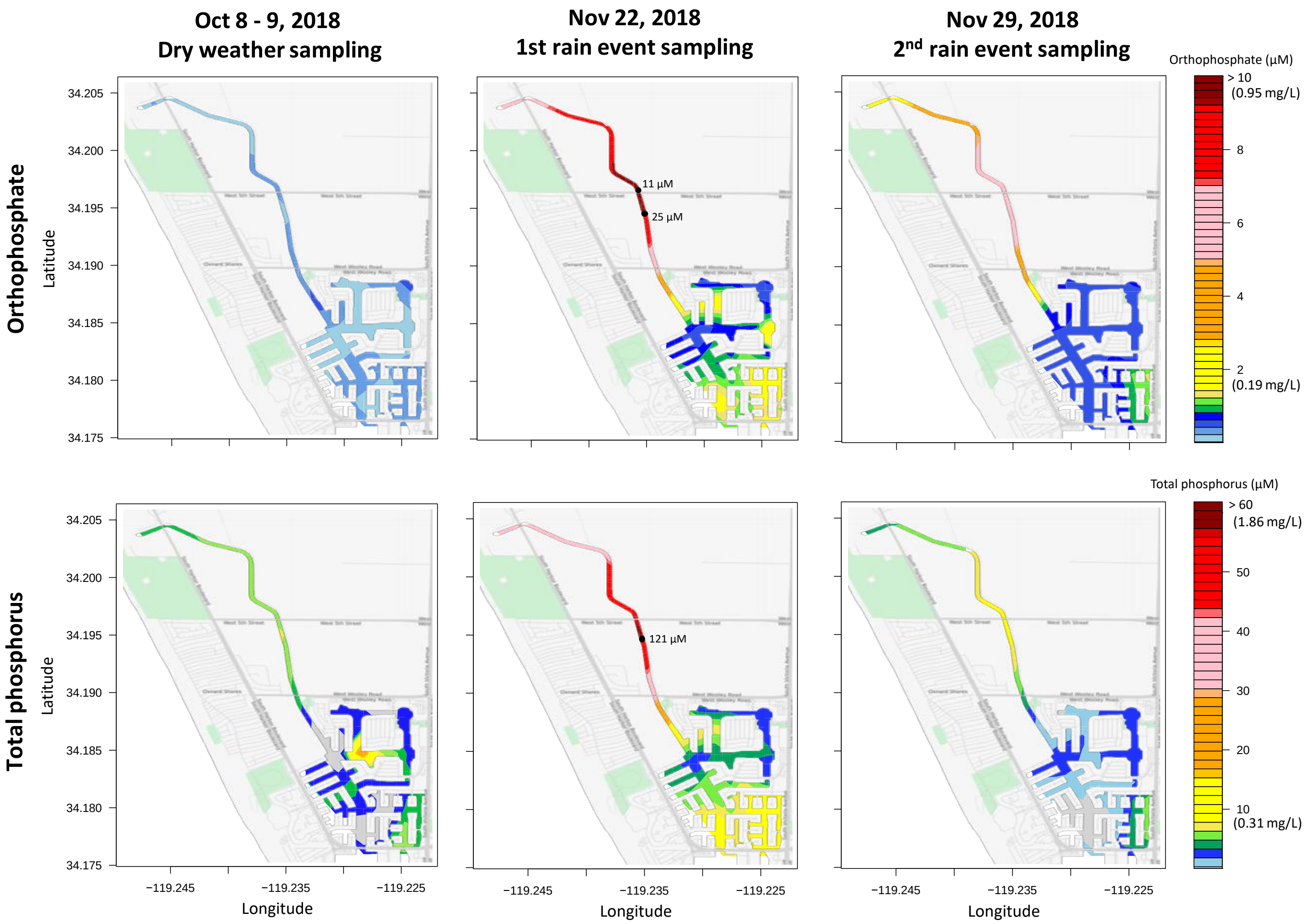


Figure 11. Color contour plots showing concentrations of orthophosphate (top row) and total phosphorus (bottom row) in near-surface water during a dry weather sampling (left column) and two sampling dates following significant rain events (middle and left columns) in CIH and Edison Canal. Orthophosphate in the water column was much higher following the two rain events (middle and right columns) than during the dry weather sampling (left column). Samples with values larger than the scale are indicated by black dots along with the concentration of the nutrient.

Table 1: Comparison of inorganic (nutrient) nitrogen (ammonium and nitrate) and phosphorus (orthophosphate) concentrations in water samples from CIH reported in this study (Refer to figs. 10, 11 for spatial patterns), and from other coastal ecosystems reported in the literature. Ammonium concentrations in CIH were not extreme, but some values were in the 'impacted' range, particularly following rain events, and some reached 'heavily impacted' values reported for Chesapeake Bay and Mazatlan Bay. Nitrate concentrations were quite high following rain events, especially in Edison Canal, indicative of 'impacted' or 'heavily impacted' conditions. Orthophosphate concentrations throughout CIH were modest during the dry weather sampling period, but were highly elevated following the rain events, particularly in Edison Canal. The highest values are commensurate with 'impacted' or 'heavily impacted' ecosystems reported in the literature. Total nitrogen (TN) and total phosphorus (TP) values were high following both rain events. 'B.D.' indicates 'Below detection' for the method used.

Location			Reference
CIH	Dry weather	NH_4^+: B.D. – 6 µM NO_3^-: B.D. – 40 µM PO_4^{2-}: 0.05 – 0.59 µM TN: 8 – 209 µM TP: 0.87 – 3.59 µM	This report
CIH	1st rain	NH_4^+: 1 – 25 µM NO_3^-: 2 – 171 µM PO_4^{2-}: 0.32 – 25 µM TN: 29 – 904 µM TP: 1 – 121 µM	This report
CIH	2nd rain	NH_4^+: 6 – 20 µM NO_3^-: 2 – 73 µM PO_4^{2-}: 0.38 – 7 µM TN: 25 – 361 µM TP: B.D. – 10 µM	This report
Northern Adriatic	Pristine	NO_x^- + NH_4^+: 0.95 - 2.42 µM PO_4^{2-}: 0.018 – 0.07 µM	Justic et al 1995
Coastal Archipelago Sea	Pristine	TN: 12 - 30 µM TP: 0.38 - 0.82 µM	Cloern 2001
Eastern Malaysia	Slightly Impacted	NH_4^+: 2.51 - 4.77 µM NO_3^-: 0.59 - 1.38 µM PO_4^{2-}: 0.27 - 0.59 µM	Lomoljo et al 2009
Northern gulf of Mexico	Slightly impacted	NO_x^- + NH_4^+: 2.23 - 8.13 µM PO_4^{2-}: 0.14 – 0.34 µM	Justic et al 1995
Eastern China	Impacted	NO_3^-: 5 – 25 µM PO_4^{2-}: <0.05 – 0.8 µM	Harrison et al 1990
Eastern Hong Kong	Impacted	NH_4^+: 2.57 – 10.13 µM NO_3^-: 1.27 - 3.4 µM PO_4^{2-}: 0.3 – 1.32 µM TN: 19 – 52 µM TP: 0.87 – 3.59 µM	Lie et al 2011

Table 1 (Cont'd): Comparison of inorganic (nutrient) nitrogen (ammonium and nitrate) and phosphorus (orthophosphate) concentrations in water samples from CIH reported in this study, and from other coastal ecosystems reported in the literature.

Location			Reference
Western Black Sea	Impacted	NO_3^-: 0.99 - 22.55 µM PO_4^{2-}: 0.13 – 26.12 µM	Cociasu et al 1996
Southern Spain	Impacted	NH_4^+: 0.08 - 15.6 µM NO_3^-: 1.09 - 4.96 µM PO_4^{2-}: 0.06 - 4.69 µM	Aguilera et al 2001
Northern Italy	Impacted	NH_4^+: 5.5 - 18.8 µM NO_3^-: 4.4 - 18 µM PO_4^{2-}: 0.3 - 0.6 µM	Nizzoli et al 2005
Coastal Baltic Sea	Impacted	NO_3^-: 2 - 11.5 µM PO_4^{2-}: 0.8 - 3.8 µM	Cloern 2001
Northern Long Island	Impacted	NH_4^+: 0.7 - 5.5 µM NO_3^-: 5.2 - 21.2 µM PO_4^{2-}: 0.4 - 1.6 µM	Hattenrath-Lehmann et al 2015
Buttermilk Bay, Cape Cod	Impacted	NH_4^+: 0.2 -11.3 µM NO_3^-: 0.2 - 38 µM PO_4^{2-}: 0.05 - 2.2 µM	Valiela & Costa 1988
San Francisco Bay	Impacted	NH_4^+: 3.2 - 11.3 µM NO_3^-: 14 - 34.4 µM PO_4^{2-}: 2.1 - 3.6 µM	Wilkerson et al 2006
San Francisco Bay	Impacted	NO_x^- + NH_4^+: 20 - 60 µM PO_4^{2-}: 1.5 - 3.2 µM	Cloern 2001
Chesapeake Bay Watersheds	Heavily impacted	NH_4^+: 2.78 – 58 µM NO_3^-: 0.48 – 50 µM PO_4^{2-}: 0.21 – 8.95 µM TN: 32 – 300 µM TP: 1.29 – 61 µM	Correll et al 1992
Eastern England River mouth	Heavily impacted	NH_4^+: 3 - 334 µM NO_3^-: 4 - 182 µM PO_4^{2-}: 0.11-37 µM	Jarvie et al 1998
Coastal Black Sea	Heavily impacted	NO_3^-: 60 - 200 µM PO_4^{2-}: <0.5 - 9 µM	Cloern 2001
Chesapeake Bay	Heavily impacted	NO_x^- + NH_4^+: < 5 - 95 µM PO_4^{2-}: 0.1 - 0.5 µM	Cloern 2001
Mazatlan Bay, South-eastern Gulf of California	Heavily impacted	NH_4^+: 0.5 - 119.84 µM NO_3^-: 0.3 - 35.74 µM PO_4^{2-}: 0.09 - 10.97 µM	Alonso-Rodriguez et al 2000

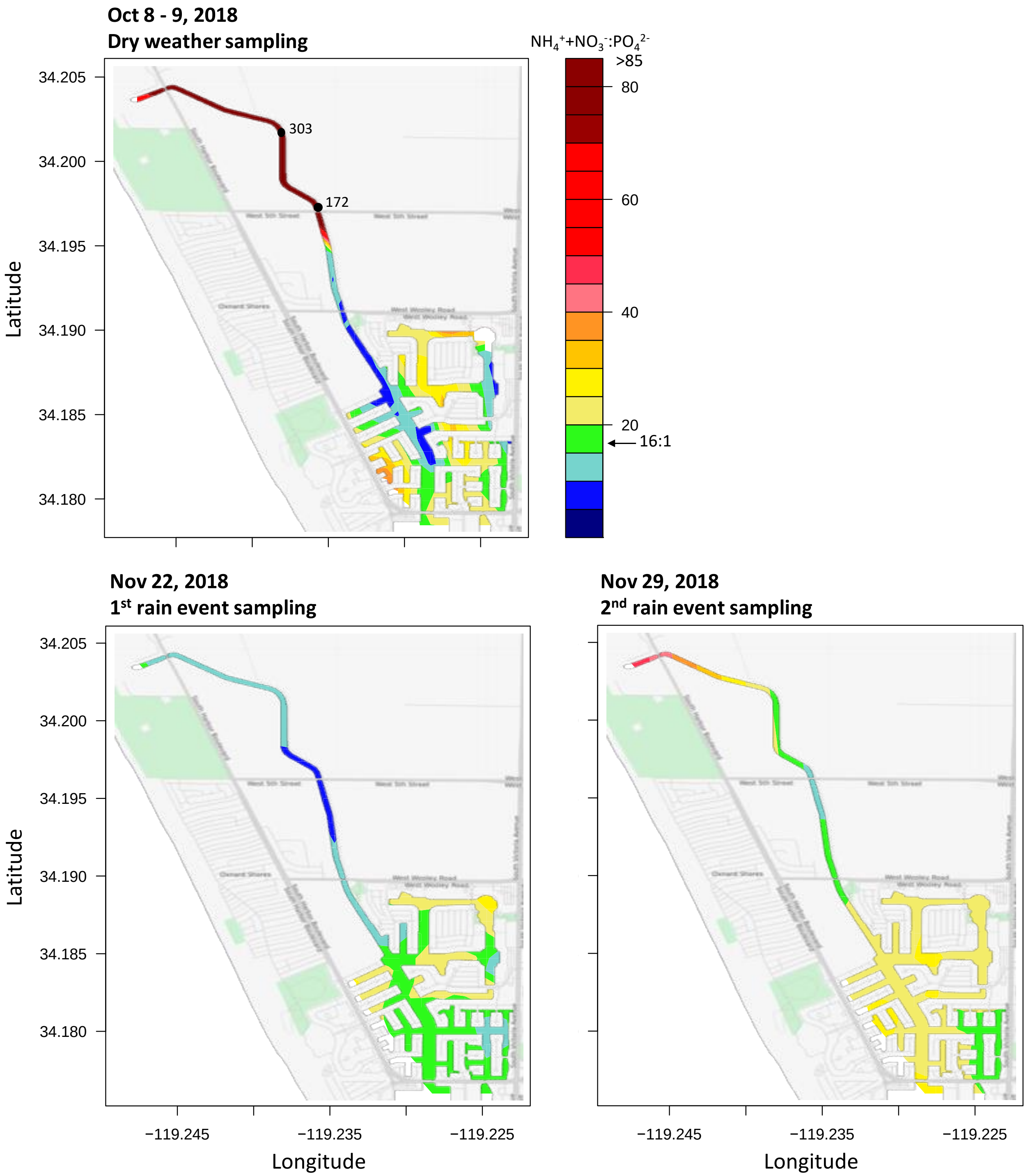


Figure 12. Color contour plots of inorganic (nutrient) nitrogen:phosphorus (ammonium+nitrate:orthophosphate) ratios in the near-surface water of CIH and Edison Canal. The Redfield Ratio of nitrogen atoms to phosphorus atoms (16:1 noted on color scale) represents an ideal balance between N and P. Ratios lower than 16:1 indicate possible nitrogen limitation of algal growth, while ratios greater than 16:1 indicate possible phosphorus limitation of algal growth. Ratios throughout most of CIH indicate potential phosphorus limitation of algal growth (i.e. are higher than a ratio of 16:1), especially during dry weather sampling in Edison Canal. Ratios in the Canal were lower following rain events, especially during the first rain event. Ratios were variable throughout CIH during the dry weather sampling.

Table 2: Comparison of inorganic (nutrient) nitrogen:phosphorus (ammonium+nitrate:orthophosphate) ratios or total nitrogen:phosphorus (TN:TP) ratios in water samples from CIH reported in this study, and from other coastal ecosystems reported in the literature. The Redfield Ratio of nitrogen atoms to phosphorus atoms (16:1) represents an ideal balance between N and P. Ratios lower than 16 indicate possible nitrogen limitation of algal growth, while ratios greater than 16 indicate possible phosphorus limitation of algal growth. Values of > 16 (phosphorus-limitation) are commonly observed in different types of coastal ecosystems, but values in Edison Canal during the dry weather sampling event (172 and 303; Refer to Fig. 12) were substantially higher than numbers reported in other studies.

Location			Reference
CIH	Dry weather	Inorganic N:P: 2.5 - 303 TN:TP: 2 – 46	This report
CIH	1st rain	Inorganic N:P: 3 - 30 TN:TP: 7 - 32	This report
CIH	2nd rain	Inorganic N:P: 13 - 55 TN:TP: 11 - 93	This report
Northern Adriatic	Pristine	Inorganic N:P: 43 – 53	Justic et al 1995
Northern gulf of Mexico	Slightly impacted	Inorganic N:P: 16 – 24	Justic et al 1995
Eastern China	Impacted	Inorganic N:P: 20 – 70	Harrison et al 1990
Eastern Hong Kong	Impacted	Inorganic N:P: 10 - 25	Lie et al 2011
Northern Long Island	Impacted	Inorganic N:P: 9.9 - 43.8	Hattenrath-Lehmann et al 2015
Chesapeake Bay Watersheds	Heavily impacted	TN:TP: 1.8 - 19	Correll et al 1992

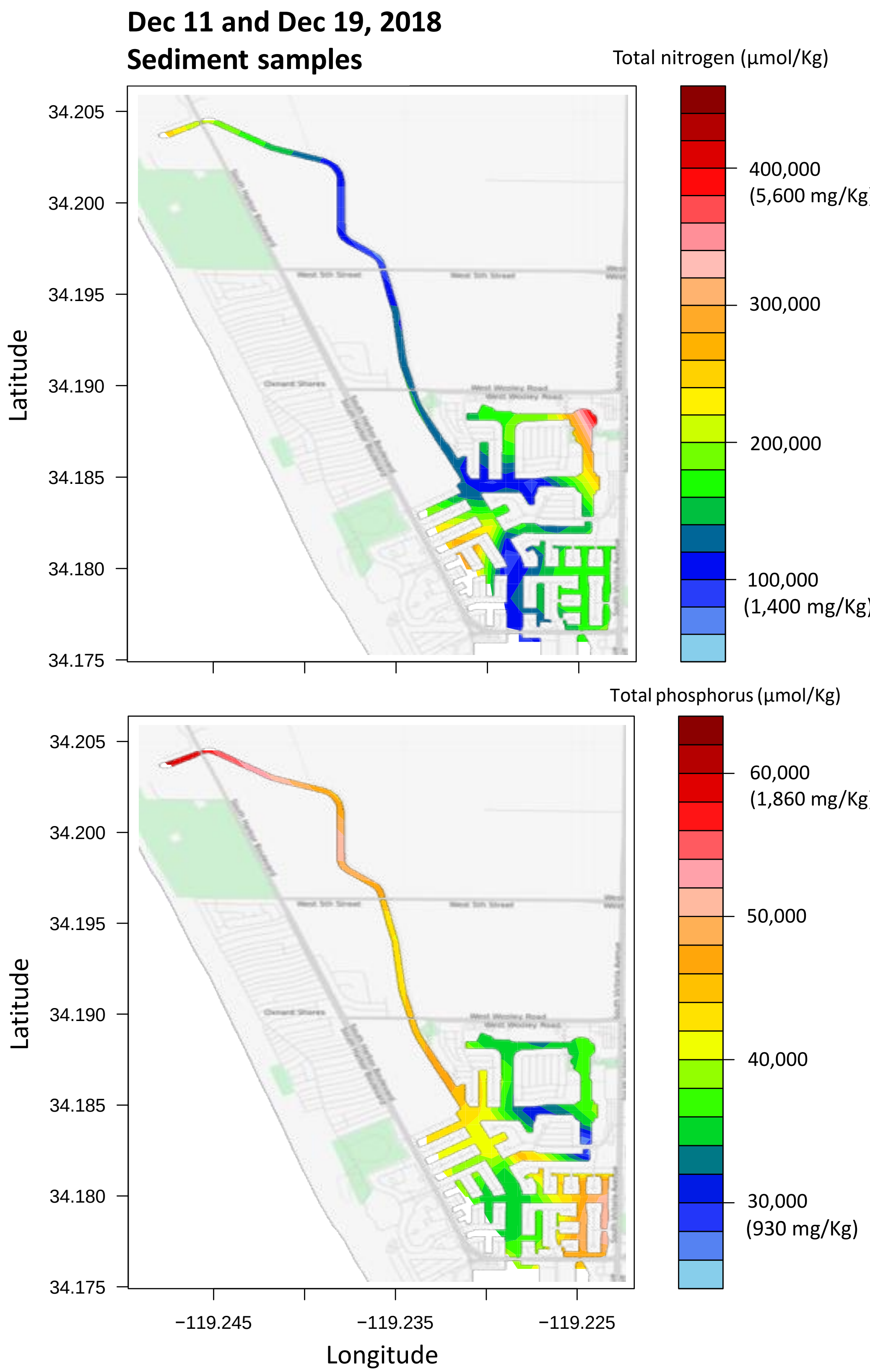


Figure 13. Color contour plots of concentrations of total nitrogen and total phosphorus in the sediments of CIH and Edison Canal on Dec 11 and Dec 19, 2018. Areas affected by anoxia in spring/summer 2018 (mostly the NE region and parts of the SW region of CIH; Refer to fig. 3) had the highest concentrations of nitrogen in the sediments. In general, that trend was reversed for phosphorus in sediments. The NE and SW regions had the lowest concentrations of phosphorus in sediments.

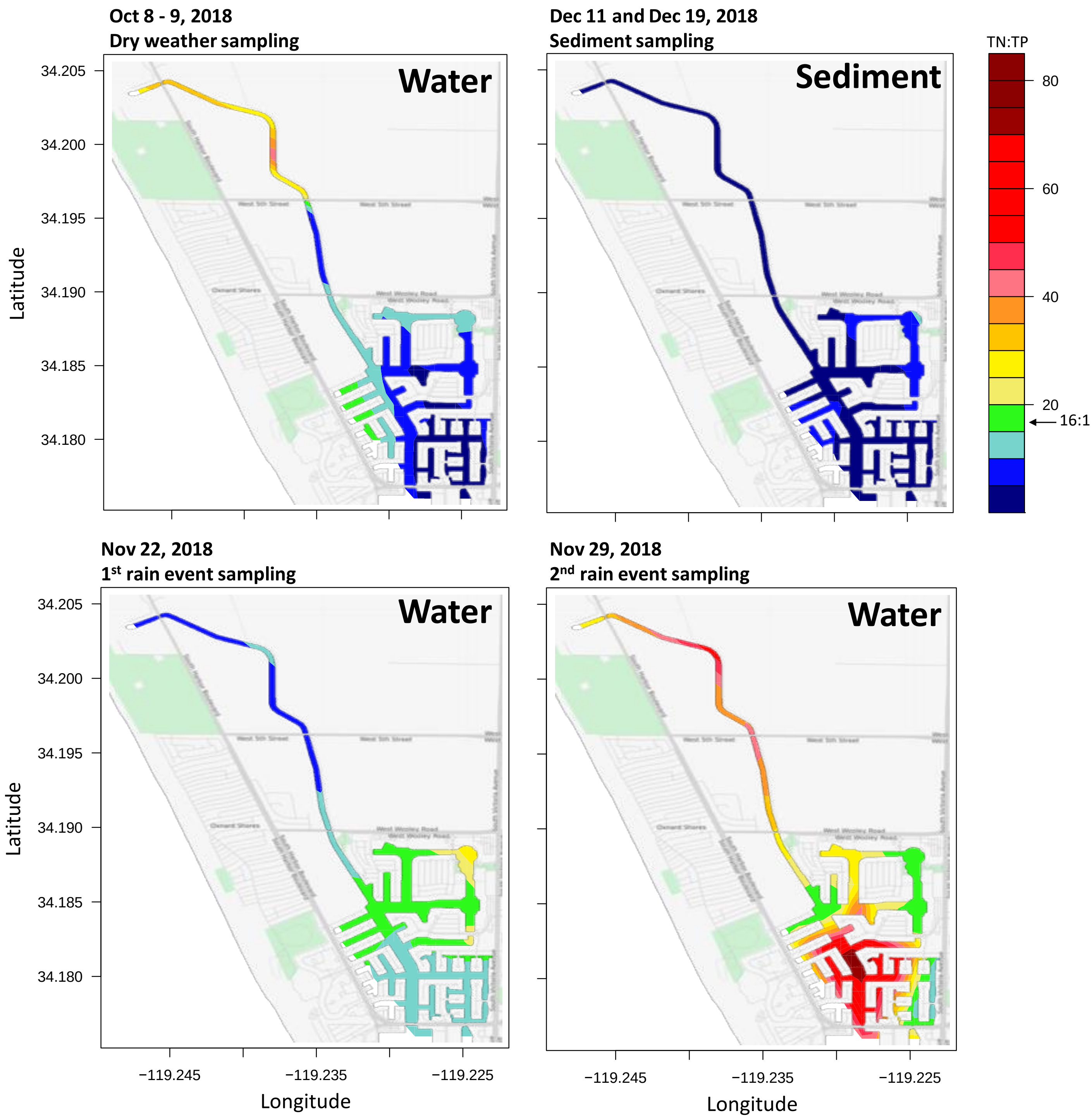


Figure 14. Color contour plots of total nitrogen: phosphorus ratios (TN:TP) in the water column during dry weather sampling (top, left), and following two rain events (bottom left and right), and in the sediments (top, right). The Redfield ratio (16:1) is indicated on the color scale. Total N:P ratios in the water were highly variable among the three sampling dates. Values following rain events tended to be much higher than values during the dry weather sampling. TN:TP ratios in sediments were consistently low across CIH and Edison Canal (top right), indicating loss of nitrogen from the sediments or effective retention of phosphorus (or both) in the sediments of this coastal ecosystem.

Table 3: Comparison of sediment total nitrogen (TN) or total phosphorus (TP) concentrations, and TN:TP ratios measured in CIH during this study, and from other coastal or river estuarine environments reported in the literature. Values for TN and TP were substantial in CIH, with values in some localities representative of 'impacted' ecosystems. TN:TP ratios in the sediments of CIH are within ranges normally observed, although published data are limited.

Location			Reference
CIH		TN: 700 – 6500 mg/Kg TP: 707 – 1960 mg/Kg TN:TP: 1 – 12	This report
Coastal			
Southern Malaysia	Pristine	TN: 165 – 621 mg/Kg	Hamad & Omran 2016
Arabian Sea	Pristine	TP: 1178 – 1395 mg/Kg	Filippelli & Cowie 2017
Shark Bay (Western Australia)	Pristine	TN: ~140 – 3500 mg/Kg TP: <31 – 620 mg/Kg TN:TP: 1 – 50	Atkinson 1987
Lagoon of Venice	Impacted	TN:784 – 5320 mg/Kg TP: 298 – 682 mg/Kg	Marcomini et al 1995
Northern Baltic Sea	Impacted	TP: 570 – 6420 mg/Kg	Puttonen 2017
Southern Baltic Sea	Impacted	TP: 1300 – 7200 mg/Kg	Berghoff et al 2000
South-western coast of Finland	Impacted	TN: 2000 – 7700 mg/Kg TP: 2000 – 2600 mg/Kg	Muller 1997
South-eastern Greece	Impacted	TN: 840 – 4890 mg/Kg TP: 91 – 4380 mg/Kg	Ladakis et al 2006
Gulf of Maine/Puget Sound	Impacted	TN: 200 – 5000 mg/Kg	Bader 1954
Southern Long Island	Impacted	TN: 200 – 4000 mg/Kg	Carroll et al 2008
Concepcion Bay, Chile	Impacted	TN: 2090 – 2540 mg/Kg	Farias et al 1996
Gulf of Finland	Heavily impacted	TP: 1860 mg/Kg	Thouvenot-Korppoo et al 2012
River estuary			
Southern Malaysia	Slightly impacted	TN: 47 – 3046 mg/Kg	Hamad & Omran 2016
Delaware River Estuary	Impacted	TP: 341 – 1026 mg/Kg	Strom & Biggs 1982

Appendix

Figure A1. Map of the sampling stations on July 6th, 2018 in the CIH.

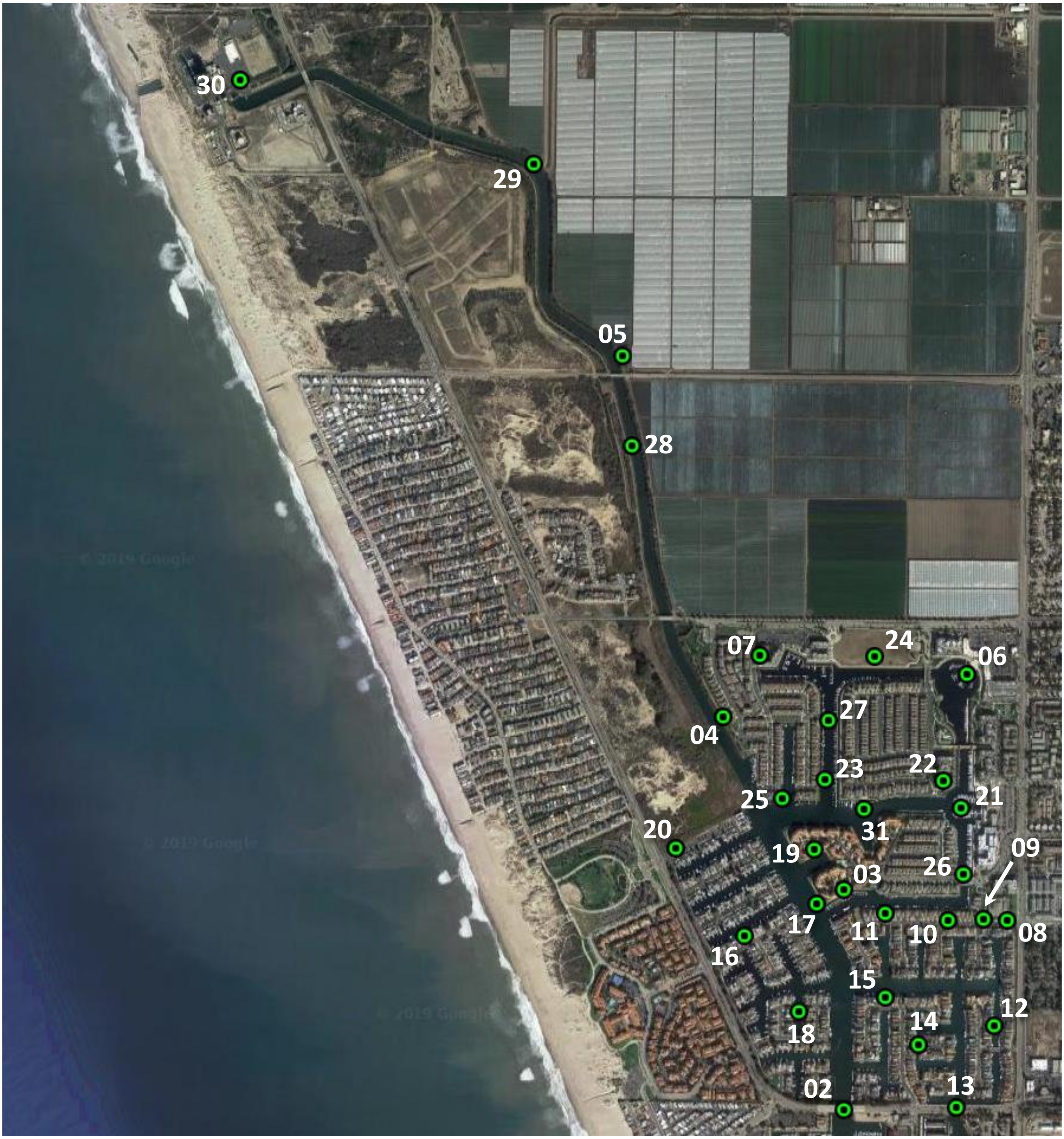


Figure A2. Map of the sampling stations for the dry weather and 2 rain sampling events in CIH and the Edison Canal.

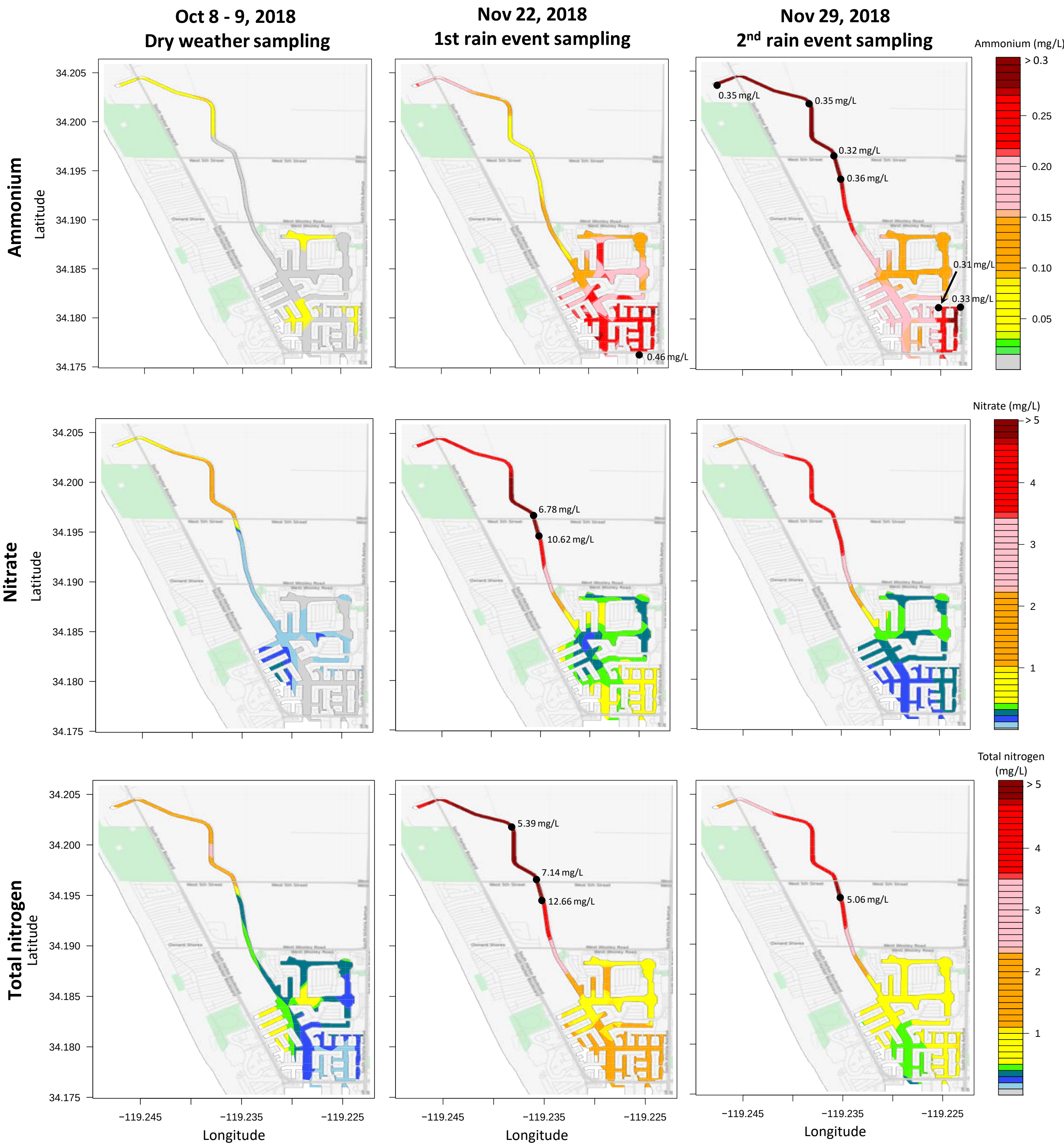


Figure A3. Color contour plots of concentrations of ammonium (top row), nitrate (middle row), and total nitrogen (bottom row) in near-surface water during a dry weather sampling (left-hand column) and following two rain events (middle and right-hand columns) in CIH and Edison Canal. Units are expressed in mg/L, and are the same values presented in units of μM in Fig. 10. Samples with values larger than the scale are indicated by black dots along with the concentration of the nutrient.

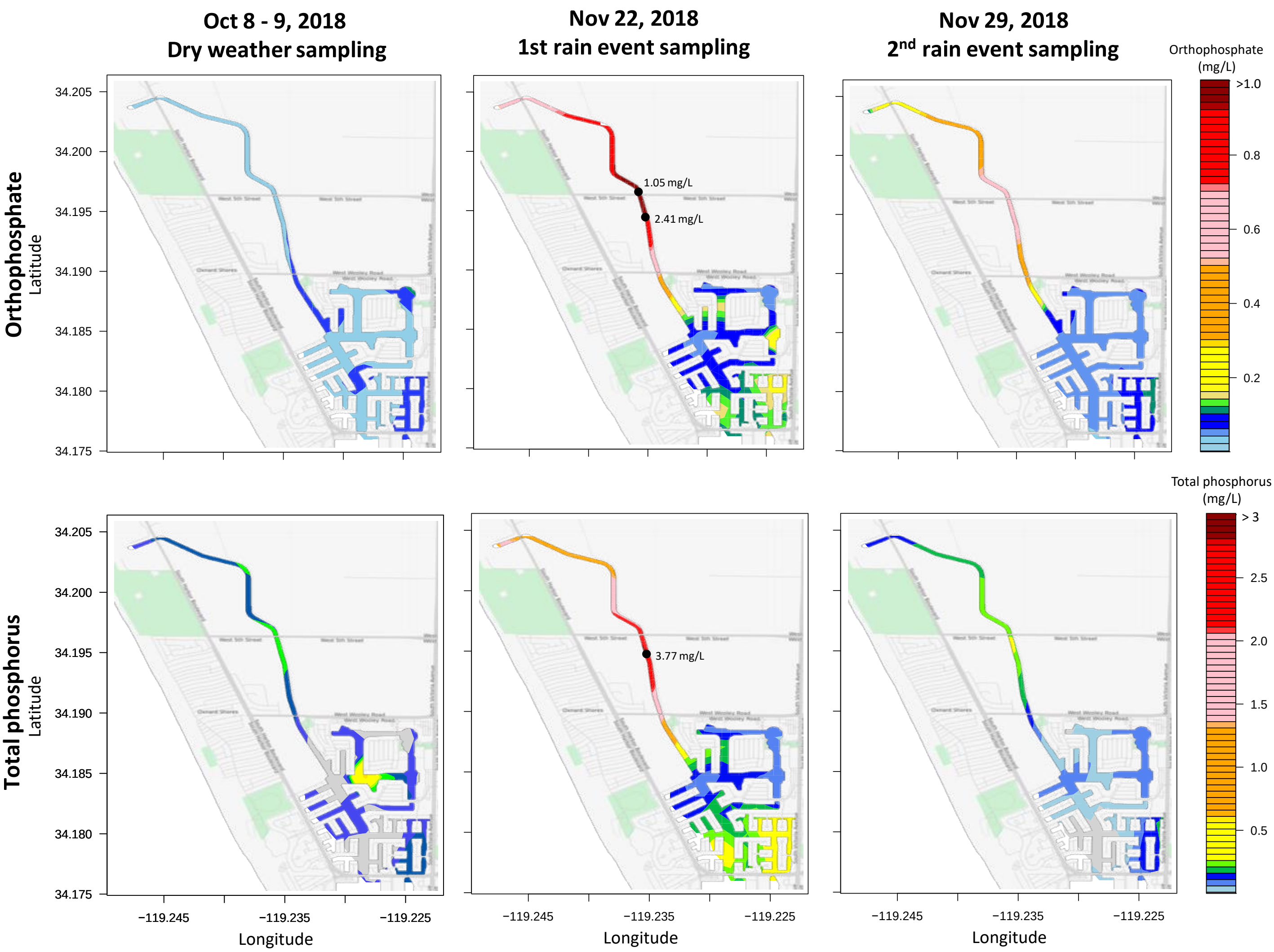


Figure A4. Color contour plots of concentrations of orthophosphate (top row) and total phosphorus (bottom row) in near-surface water during a dry weather sampling (left-hand column) and following two rain events (middle and right-hand columns) in CIH and Edison Canal. Units are expressed in mg/L, and are the same values presented in units of µM in Fig. 11. Samples with values larger than the scale are indicated by black dots along with the concentration of the nutrient.

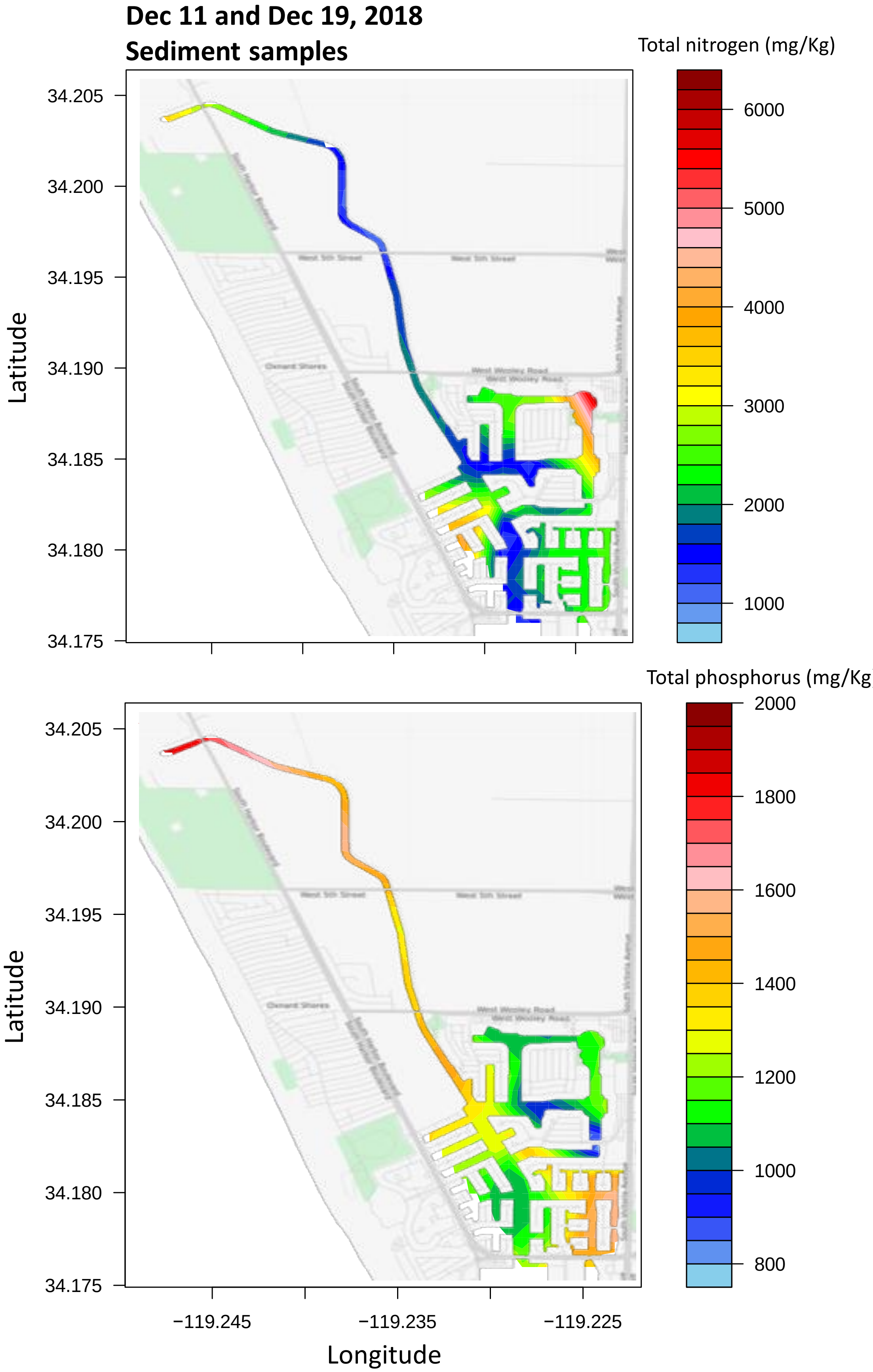


Figure A5. Color contour plots of concentrations of total nitrogen and total phosphorus in the sediments in the CIH and Edison Canal on Dec 11 and Dec 19, 2018. Units are expressed in mg/Kg, and are the same values presented in units of µM in Fig. 13.