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Date:	October 2, 2018
To:	Nordic Aquafarms
From:	Nathan Dill, P.E.
Subject:	Far-field Dilution of Proposed discharge

This memorandum provides a summary of the estimated far-field plume behavior and dilution of wastewater discharge from the proposed Nordic Aquafarms Recirculating Aquaculture System (RAS) into Belfast Bay, Maine. Far-field transport, dispersion, and dilution of the RAS wastewater has been investigated through a combination of two-dimensional hydrodynamic modeling with the ADvanced CIRCulation Model (ADCIRC)[1] and numerical particle tracking with the Maureparticle[2] particle tracking model. Initial near-field dilution of the discharge was investigated with the Cornell Mixing Zone Expert system (CORMIX) model and is described in a separate memorandum[3].

FAR-FIELD DILUTION APPROACH

Near-field dilution modeling performed with CORMIX assumes a steady-state for the RAS wastewater discharge and ambient conditions. In tidal environments where the ambient current may change significantly within a few hours, the steady-state assumption is only valid for near-field mixing processes on relatively short time scales (e.g. less than an hour or so). Furthermore, the near-field modeling with the steady-state assumption may overestimate long-term dilution because it does not consider the potential for recirculation of the discharge plume with tidal reversals. For example, a plume that develops during an ebbing tide may reverse direction and travel past the outfall during the following flood tide, effectively increasing the background concentration of wastewater constituents. Over many tidal cycles the background concentration achieves a dynamic equilibrium condition where the rate of wastewater discharge is in balance with the flushing characteristics of the receiving waterbody and dispersion of the plume. To better understand far-field behavior of the wastewater plume, a two-dimensional hydrodynamic

[1] Luettich, R.A., J.J. Westering, N.W.Scheffner, 1992. "ADCIRC: An Advanced Three-Dimensional Circulation Model for Shelves, Coasts, and Estuaries, Report 1, Theory and Methodology of ADCIRC-2DDI and ADCIRC-3DL". Technical Report DRP-92-6, Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station

[2] Dill, N. L., 2007. "Hydrodynamic modeling of a hypothetical river diversion near Empire, Louisiana". LSU Master's Theses. 660. https://digitalcommons.lsu.edu/gradschool_theses/660

[3] Ransom Consulting, 2018. Near-field Dilution of Proposed Discharge Update, Memorandum to Nordic Aquafarms, September 17, 2018.

modeling and particle tracking approach is employed. A numerical hydrodynamic model is used to estimate time-dependent and spatially variable depth averaged currents. The current velocity field from the hydrodynamic model is then used to drive a particle tracking model that is in turn applied to estimate dilution and concentrations.

TWO-DIMENSIONAL HYDRODYNAMIC MODELING

An existing ADCIRC model, previously developed by Ransom[4], has been used to simulate tidal circulation in Belfast Bay to aid in evaluation of the far-field behavior of the effluent plume. ADCIRC is a state-of-the-art numerical model that solves the Generalized Wave Continuity Equation (GWCE) form of the Shallow Water Equations (SWE). The SWE are set of mathematical equations that govern the motion of fluid in the ocean and coastal areas through laws of conserved mass and momentum. ADCIRC employs the finite element method on an unstructured triangular computational grid that allows for high spatial resolution in coastal areas. ADCIRC's capabilities include simulation of water level and current velocity driven by astronomical tides, and wind and atmospheric pressure. ADCIRC has been applied in the 2-Dimensional Depth Integrated (2DDI) mode and has been forced with astronomic tides on the open ocean boundary and 280 cubic meters per second inflow at the Penobscot River Boundary. No wind forcing was included in the model simulation for this effort, which is generally considered to be conservative with respect to mixing processes. Figure 1 shows the extent of the model domain and inset detail of the model's triangular unstructured grid near the proposed outfall location.

ADCIRC Model Validation

The ADCIRC model was used to simulate tides during the period from June 20, 1999 to August 4, 1999 to provide a representative data set of tidal current velocities for this effort. This time period was selected because water level observations are available at the nearby National Oceanic and Atmospheric Administration National Ocean Service (NOAA NOS) station at Fort Point, Maine. The relative location of the Fort Point tide station and proposed outfall location is shown in Figure 2. A comparison of observed water levels to modeled water levels at the Fort Point Station is shown in Figure 3. In addition, a comparison of modeled water levels to harmonically predicted high and low tides at the subordinate NOS tide station at Belfast is shown in Figure 4. Visual inspection of the water level time series suggests good agreement between model results and observations. Although specific observations of tidal currents are not available in the vicinity of the proposed outfall location, the simulation of accurate water levels suggests that depth averaged current velocities are reasonable.

[4] Ransom Consulting, Inc. 2017. Present and Future Vulnerability to Coastal Flooding at Grindle Point and the Narrows. Report prepared for the Town of Islesboro, Maine, August 21, 2017.

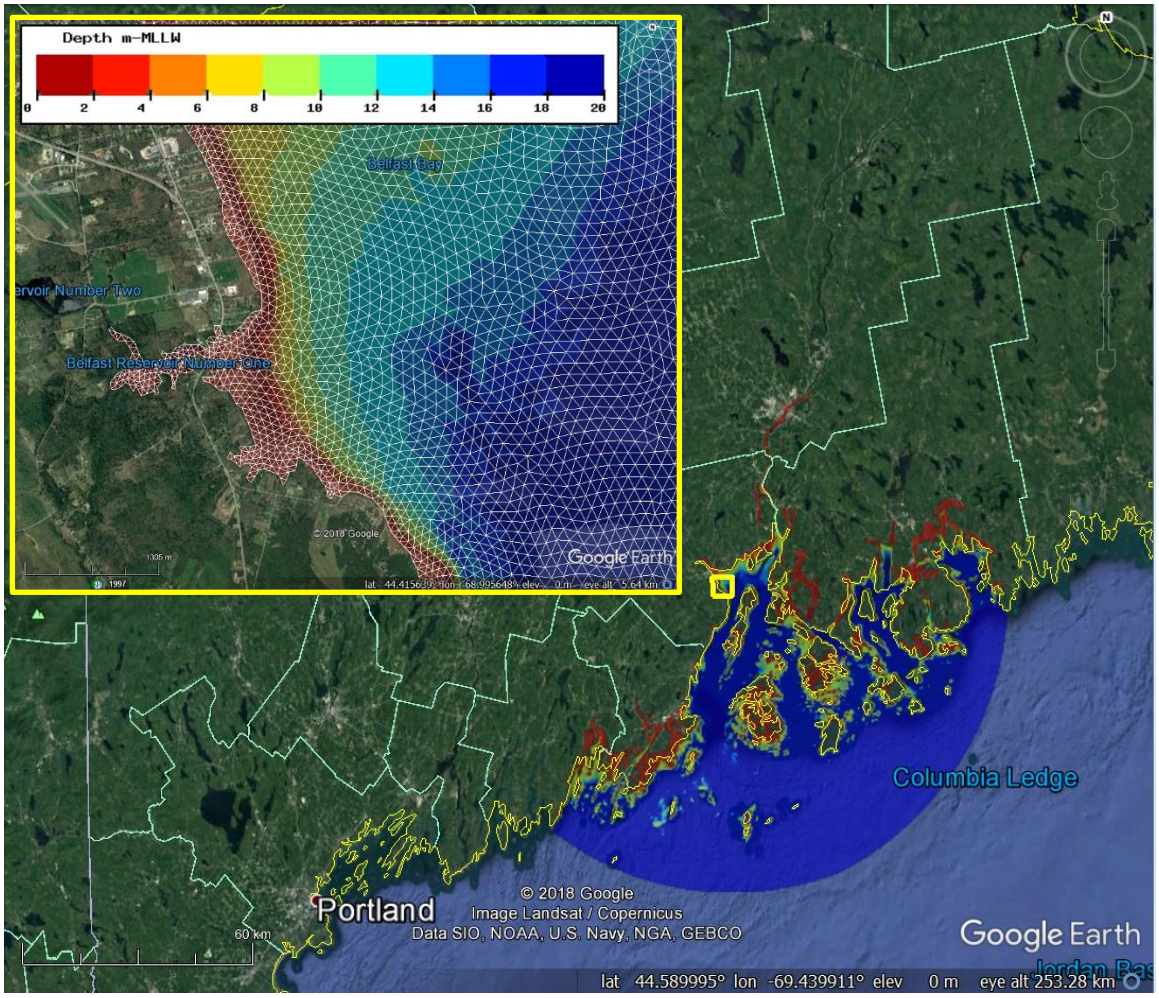

Figure 1. Penobscot Bay ADCIRC model domain and detail in Belfast Bay.

Figure 2. Location of NOAA NOS stations at Belfast (8415191) and Fort Point (8414721), and approximate location of proposed outfall.

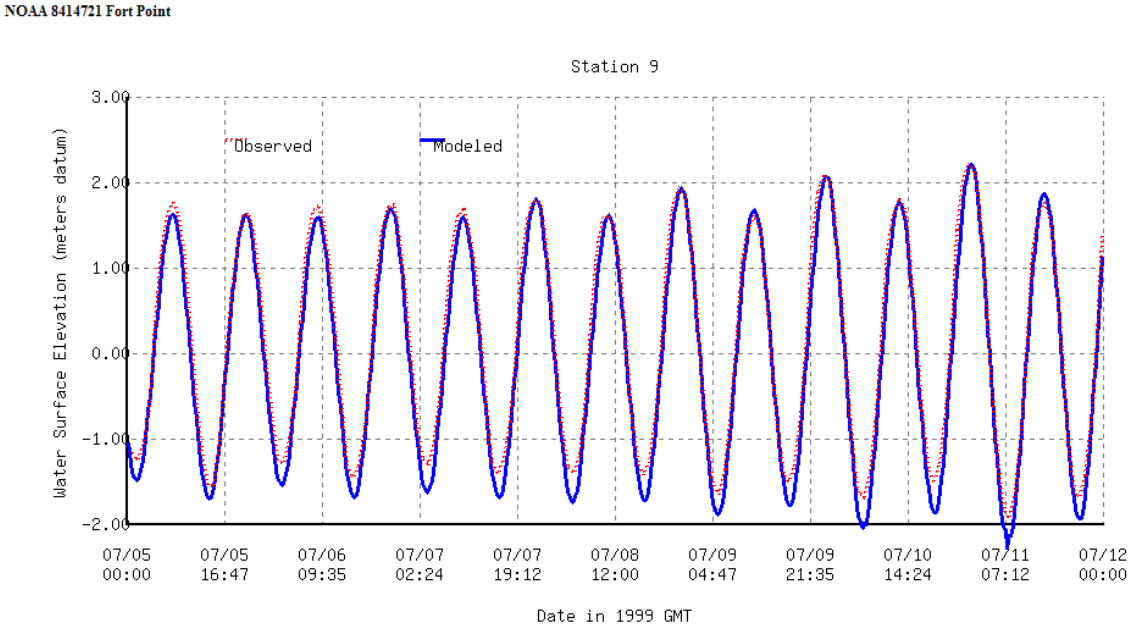

Figure 3. Comparison of modeled water level and observed hourly water level at NOS station 8414712 at Fort Point, Maine during a portion of the simulation period.

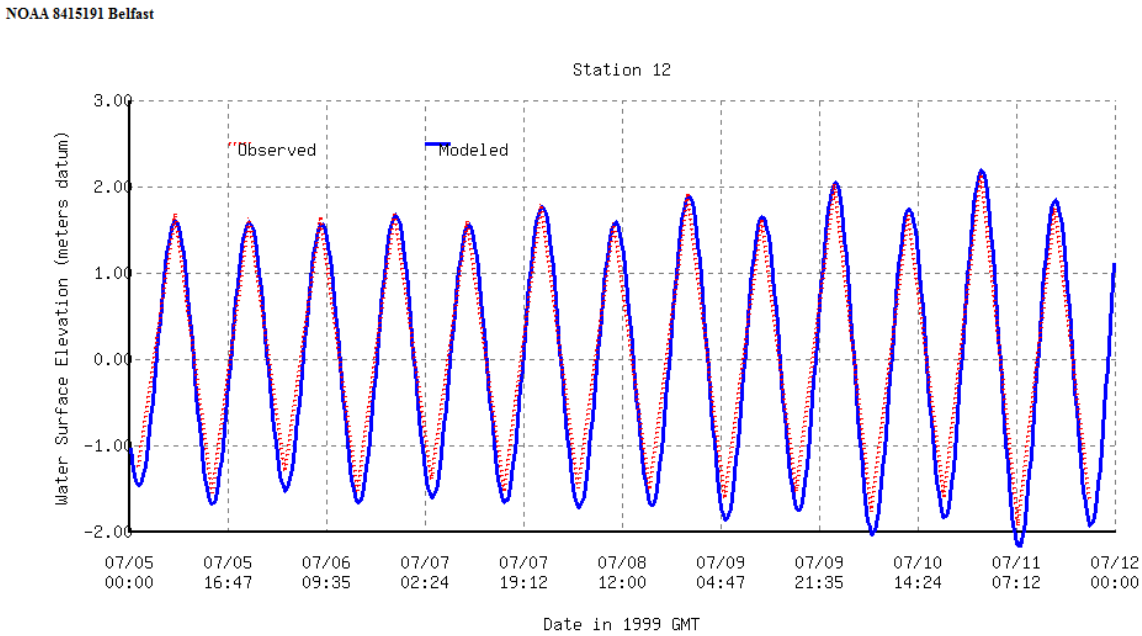

Figure 4. Comparison of modeled water level and harmonically predicted high-low tide data at NOS station 8415191 at Belfast, Maine during a portion of the simulation period.

PARTICLE TRACKING FAR-FIELD DILUTION

The particle tracking model was run with the following configuration and assumptions:

- Particles are released at a constant rate from the outfall location. Initial particle locations were randomly generated along a 50-meter line that extends east from -68.972526 degrees Longitude and 44.395004 degrees latitude. This release configuration is consistent with effluent discharge and initial dilution from the multi-port diffuser considered in the CORMIX modeling.
- Particles are released at a rate of 1 per 30 seconds over a period of 28 days, resulting in a total of 80640 particles that are tracked during the simulation.
- An effluent flow rate of 0.338 m^3/s is assumed such that each particle represents the mass of effluent constituents (e.g. Total Nitrogen) contained within 10 m^3 of effluent.
- A horizontal eddy diffusivity of 2 m^2/s is simulated through random walk displacement.
- Particles are tracked using the 2nd order Runge-Kutta method to integrate the dynamic depth averaged current velocity field.
- For dilution calculations it is assumed that the plume will become well mixed within upper portion of the water column in far-field timescales, which is assumed to have a 10-meter thickness. This assumption is reasonable during stratified conditions in the warmer seasons of the year, and conservative during winter months when CORMIX predicts full vertical mixing.
- Dilution is calculated by counting the number of particles within each model grid element and dividing the effluent volume associated with the particles by the sum of ambient volume in the upper layer and effluent volume within grid element.

- Effluent Concentrations may be calculated using the following equation using initial and background concentrations listed in Table 1; where *C* is the concentration corresponding to dilution, *S*. *Cs* is the background concentration, and *Cd* is the effluent concentration[5].

$$C = Cs + \frac{1}{S}(Cd - Cs)$$

- The effects of wind and/or waves on the mixing and current velocity field is neglected. Winds and waves tend to enhance turbulence, increasing mixing and dilution. Neglecting the effect of wind and waves tends to produce conservative estimates of dilution and plume concentrations.
- No uptake or decay of nutrients is considered, which is also considered to be conservative, as some level of uptake or decay is likely.

Table 1. Effluent Concentrations for proposed discharge and background concentrations.

	Total Suspended Solids (TSS)	**Biochemical Oxygen Demand (BOD)**	**Total Nitrogen (TN)**	**Ammonium Nitrogen (NH_4)**	**Phosphorus (P)**
Daily Discharge (kg)	185	162	673	0.07	5.8
Concentration (mg/l)	6.33	5.55	23.02	0.0024	0.20
Assumed Background Concentration (mg/l)	17	2.0	0.17†±	0.075†	0.013

†Not detected at the reporting limit for all samples
±Background concentration as per communication with MEDEP

RESULTS AND DISCUSSION

Dilution of the proposed RAS wastewater was determined at hourly intervals throughout the 28-day particle tracking simulation. Visualization of the model results show that after approximately 14 days of continuous release a dynamic equilibrium condition is reached where the rate of discharge is effectively balanced by diffusion and dispersion rates. Figure 5 shows a sequence of snapshots of the base 10 logarithm of the dilution throughout a typical tidal cycle near the end of the particle tracking simulation after the plume has had sufficient time to reach a dynamic equilibrium state. Although it varies somewhat throughout the tidal cycle and with neap and spring tidal phases, the minimum dilution near the center of the plume is approximately 30. The maximum dilution shown in the figure is approximately 300 at the edge of the colored area shown in Figure 5. Outside this area the dilution is greater. The dilution results may be used to estimate the concentration of RAS wastewater constituents using the above equation given effluent and background concentrations.

[5] Fischer, H.B., E.J. List, R.C.Y. Koh, J.Imberger, N.H.Brooks,. 1979. Mixing in Inland and Coastal Waters. Academic Press Inc., New York, NY. 483 p.

It is our understanding from communication with Maine DEP that there are no specific regulatory criteria for nutrient concentrations in Belfast Bay. However, recent investigations in the Great Bay Estuary by the New Hampshire Department of Environmental Services (NHDES) suggest that nitrogen may act as a limiting nutrient with respect to undesirable macroalgae and phytoplankton growth. NHDES also found correlation between nitrogen and dissolved oxygen concentrations suggesting a threshold above which nitrogen concentrations may lead to hypoxic conditions. Data from the Great Bay suggest that median total N concentrations should be less than 0.34-0.38 mg/l to prevent the replacement of eelgrass habitat with macroalgae growth. Furthermore, correlation of median total N concentrations with dissolved oxygen measurement suggests that total N should be less than or equal to 0.45 mg/l to prevent hypoxic conditions with dissolved oxygen concentrations less than 5 mg/l[6]. Although characteristics of the Great Bay Estuary are different than the Belfast Bay - with respect to temperature, freshwater input, tidal prism, and stratification, for example – the Great Bay criteria may be considered as guidance in the absence of specific criteria for Belfast Bay.

The State of Maine has identified two locations near the proposed outfall location where eelgrass beds are present. The location of eelgrass beds, the proposed outfall, and the median total N concentration are shown in Figure 6. The median total N concentration was determined by calculating total N concentration from hourly dilution snapshots over the final 14 days of the simulations. Values for each snapshot were then rank ordered and the 50th percentile was taken as the median.

Overall, the results indicate that the eelgrass beds will not be impacted by concentration greater than 0.3 mg/l and that the bay will not generally be exposed to total N concentrations greater than about 0.4 mg/l. However, it is important to understand that the model results are only an approximation based on numerous simplifying assumptions listed above. Actual conditions may vary from these assumptions such that actual concentrations are different than predicted. For the most part, conservative assumptions have been made so that the predicted concentrations will tend to be greater than concentrations influenced by real world conditions. For example, the model neglects the effects of wind and waves on the current velocity and mixing. These effects would tend to increase turbulence leading to increased diffusion and dispersion of the plume, and the reduce concentrations. Also, real world conditions will lead to uptake and decay of nutrients, which would tend to reduce concentrations compared to the model results where no decay has been assumed.

The information presented here is based entirely upon numerical modeling with limited knowledge of the in-situ conditions at the proposed outfall site. It is important to understand that hydrodynamic modeling is not an exact science. As such, any predictions presented here should be considered only as estimates of the proposed dilution and plume behavior. Numerous assumptions and simplifications have been made in this analysis, which contribute to significant uncertainty in the modeling results. In general, these simplifications and assumptions are reasonably conservative, such that errors would tend to over-predict negative impacts. However, it is possible that predictive error could under-estimate impacts. Thus, it is recommended that a

[6] New Hampshire Department of Environmental Services. 2009. Numeric Nutrient Criteria for the Great Bay Estuary. Prepared by Philip Trowbridge, P.E., June 2009. 73 pages.

field data collection program be designed and implemented to provide site specific data for further analysis, and to validate the accuracy of model results.

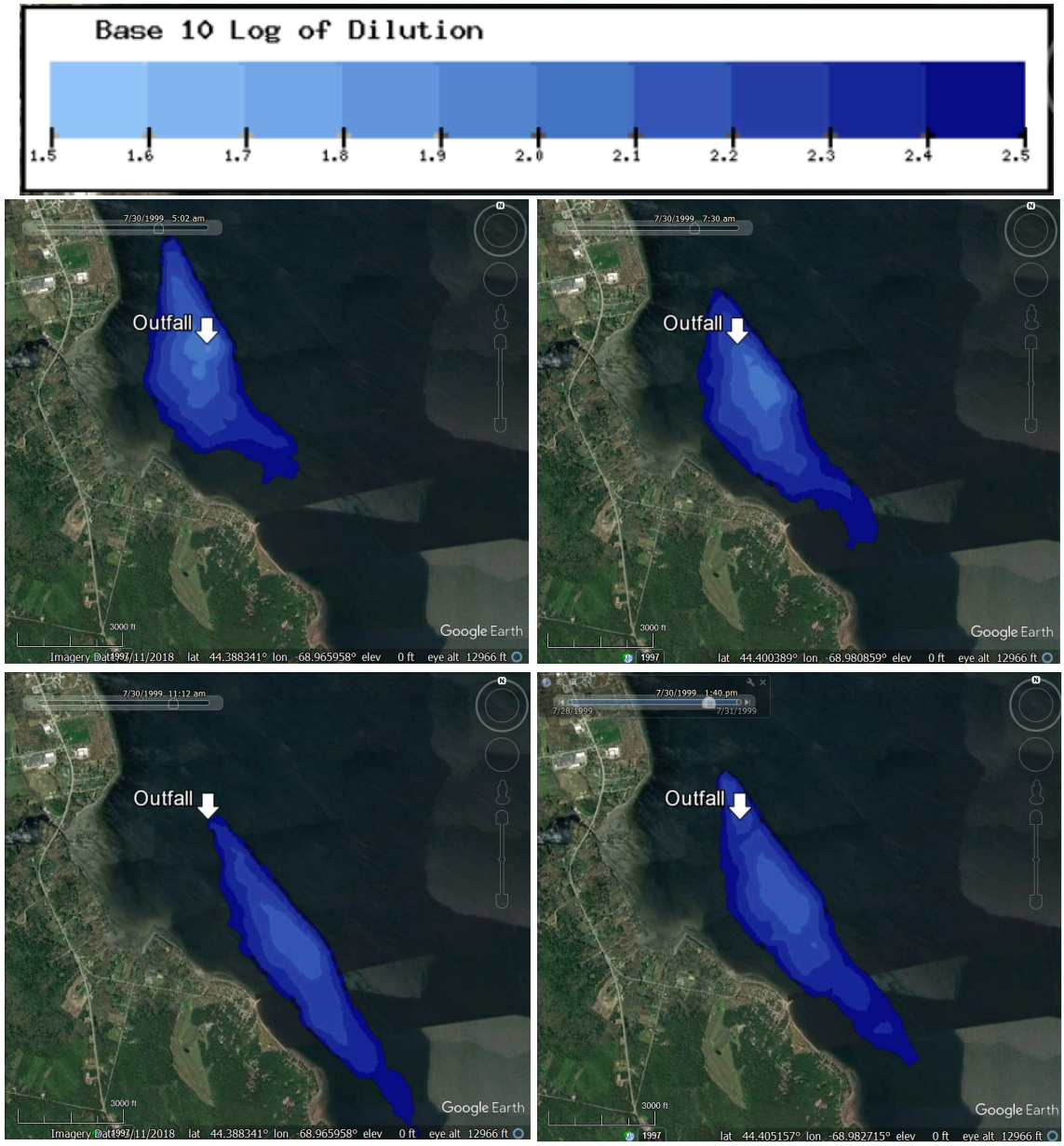

Figure 5. Snapshots of plume dilution throughout a typical tidal cycle. high slack (upper left), mid-ebb (upper right), low slack (lower left), mid-flood (lower right).

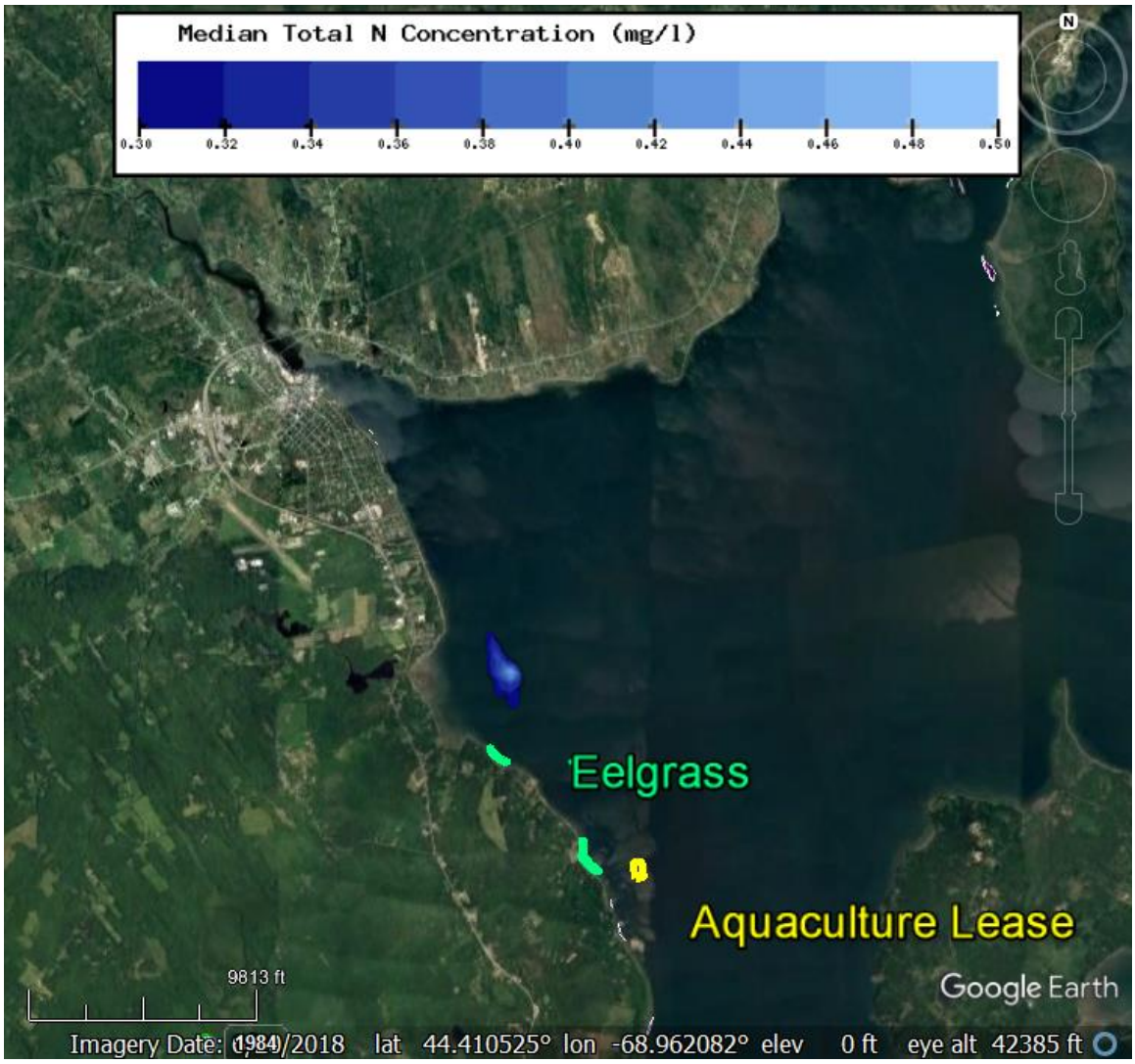

Figure 6. Time Averaged Median Total Nitrogen Concentration