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Gulf Region

Canadian Science Advisory Secretariat
Science Advisory Report 2021/023

VALIDATION OF DISSOLVED OXYGEN (DO) AS MARINE ENVIRONMENTAL QUALITY (MEQ) MEASURE OF NUTRIENT LOADING STATUS OF ESTUARIES

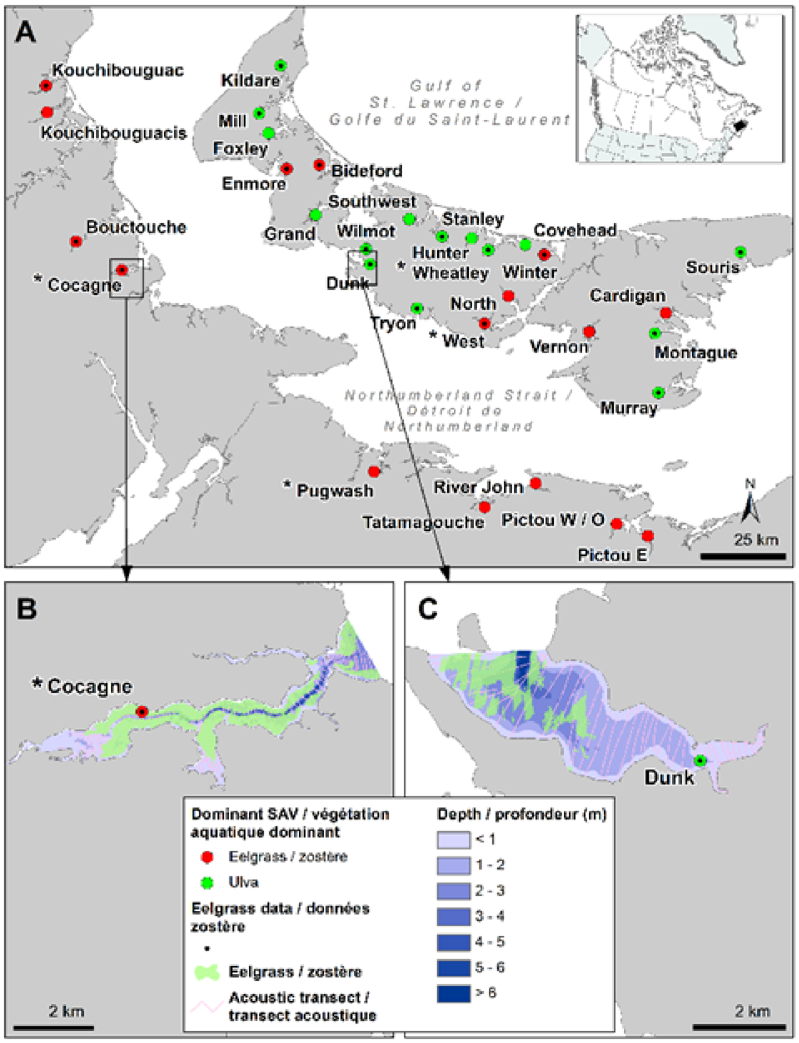

Figure 1. Study area in the context of eastern North America. A) estuaries that were studied in the southern Gulf of Saint Lawrence; Ulva *spp. dominated estuaries are denoted by green circles, and* Z. marina *dominated estuaries by red circles (a convention that is maintained throughout the document). Estuaries where eelgrass data were collected are denoted by a black dot. Estuaries with an asterisk represent Marine Environmental Quality (MEQ) monitoring sites where data are collected annually, B) and C) insets demonstrate the approximate location of the dissolved oxygen probes and show acoustic transects and modelled eelgrass coverage at two representative sites.*

Context:

Eutrophication, the biological response to nutrient enrichment, is a well-studied process that poses a threat to coastal ecosystems around the world, including the southern Gulf of St. Lawrence (sGSL). Despite an understanding of the mechanisms that contribute to nutrient impacts, there is no universal method for their quantification or monitoring. Estuaries in the sGSL are characterized by vast eelgrass meadows that become displaced by algae in response to increased nutrient loading. While eelgrass is an effective indicator of ecosystem health, it is sensitive to stress from a variety of potential sources. Consequently, it can be difficult to link changes in eelgrass coverage to a specific stressor. Therefore, there is some ambiguity when relating changes to eelgrass coverage with nutrient impacts specifically. Conversely, dissolved oxygen may be a more sensitive indicator of nutrient impact since it reflects primary production by providing the balance of oxygen production via photosynthesis and oxygen consumption through respiration. DFO Gulf Region Aquatic Ecosystems Management requested advice as to the suitability of dissolved oxygen and eelgrass coverage as indicators of trophic status of estuaries and whether they could be applied to a Marine Environmental Quality measure (MEQ).

This Science Advisory Report is from the Regional Advisory Meeting of February 23-24, 2021 on the Validation of DO as MEQ measure of nutrient loading status of estuaries. Additional publications from this meeting will be posted on the [Fisheries and Oceans Canada (DFO) Science Advisory Schedule](#) as they become available.

SUMMARY

- The southern Gulf of St. Lawrence is a region characterized by multiple estuaries experiencing similar weather (e.g. freezes over in winter), geography, and lithology, with relatively small watersheds (10s-100s km^2) that have low freshwater input that ultimately empty into either the Northumberland Strait or the Gulf of St. Lawrence.
- Estuaries and bays of the southern Gulf of St. Lawrence, like many places around the world, are sensitive to impacts from excess nutrients, including loss of eelgrass and the occurrence of hypoxia/anoxia.
- The monitoring indicator proposed here, termed “Eutrophic Time”, is defined as the percent of time an upper estuary spends <4 mg/L (hypoxia/anoxia) and >10 mg/L (supersaturation), and is the latest iteration using dissolved oxygen as the endpoint of interest.
- Eutrophic Time reflects the relative trophic status of upper estuaries and was effective at discriminating between those dominated by eelgrass (*Zostera marina*) or macroalgae (*Ulva* spp.). Further, a threshold for Eutrophic Time was interpolated at 35%, based on an apparent inflection point in habitat type from eelgrass to macroalgae.
- Nitrate-N loading and Water Residence Time were highly predictive (R^2 = 0.81) of Eutrophic Time but less predictive of hypoxia/anoxia (R^2 = 0.63).
- This relationship was exploited for *Ulva*-dominated estuaries to develop nitrate-N loading targets to move towards a Eutrophic Time threshold (0.35) consistent with a habitat shift toward eelgrass and an improvement in water quality.
- Estimated eelgrass coverage in the entire estuary was inversely correlated with nitrate-N loading (though not Water Residence Time), with eelgrass coverage declining as nitrate-N loading increased.
- Eutrophic Time can be used to identify estuaries that should benefit ecologically, including improved water quality and eelgrass recovery and conservation, and coarse nitrogen reduction targets are provided to do so.

- There was insufficient long-term data to provide a recommendation towards an effective monitoring cycle. Monitoring cycles should reflect the needs of the monitoring program to inform effective decision making and adaptive management.

INTRODUCTION

Southern Gulf of St. Lawrence (sGSL) estuaries and bays, like many places around the world, are sensitive to impacts from excess nutrients (eutrophication). Increased nutrient loading to coastal systems can have negative impacts, including loss of biodiversity, seagrass coverage and if anoxia occurs and is sustained, mass mortality of fauna. Given the potential severity of nutrient impacts, it is imperative that any monitoring program be capable of accurately assessing these impacts and that there is a quantitative link between nutrient loading and any response indicator.

Establishing indicators for assessing ecosystem habitat quality is critical for developing cost-effective monitoring programs that can inform decision-making. Consequently, effective indicators must have characteristics that promote initial adoption and persistence as part of a sustained monitoring effort (Rice and Rochet 2005). Ideally, such indicators should be biologically relevant and quantitatively measurable to provide a meaningful and useful tool for monitoring. Most importantly, there must be a mechanistic relationship between the indicator and the ecosystem stressor such that changes to the indicator are the result of changes in the stressor (i.e. that the indicator is sensitive and specific to changes with the stressor). Thus, dissolved oxygen presents as an indicator with great potential.

The monitoring indicator presented herein is the third iteration using dissolved oxygen as the primary endpoint to capture nutrient impact. Bugden et al. (2014) performed the first iteration of relating dissolved oxygen monitoring to nitrogen loading in the sGSL, however while they assumed that the majority of nitrogen enters the estuary from land via freshwater, and that the risk of developing low oxygen conditions increases with water residence time, they did not quantify these important measures. The Northumberland Strait Environmental Monitoring Partnership (NorSt-EMP) – a group consisting of Indigenous groups, stakeholders, academics, and provincial (PEI and NB) and federal governments improved dissolved oxygen monitoring in the region for the development of a more refined dissolved oxygen model. Their approach was to use optical dissolved oxygen loggers that were deployed in the upper portion (i.e. where nutrient impacts are typically most severe at approximately the upper 10% of the area of a given estuary) of 15 estuaries across NB, NS, and PEI. This data enabled greater discrimination between sites of varying levels of nutrient impact.

Given that nutrient impacts are a persistent issue in the sGSL region, and that a successful monitoring approach was already established for this area (Coffin et al. 2018; van den Heuvel et al. 2019), Department of Fisheries and Oceans Canada (DFO) Gulf Region Aquatic Ecosystems Management requested validation of this approach through an increase in scope of that monitoring program in terms of years of data acquisition, and number of sites. As such, the overarching goal of this Canadian Science Advisory Secretariat (CSAS) process was to confirm that dissolved oxygen monitoring and eelgrass coverage surveys, building upon previous work, serve as effective endpoints for assessing eutrophication.

ASSESSMENT

Objectives

Objective 1: The main advice requested is to define the dissolved oxygen threshold, or dissolved oxygen range, to be included in the Gulf's Marine Environmental Quality (MEQ) measure. The intent is to include dissolved oxygen as the main indicator in a regional monitoring program to assess the trophic status of estuaries and evaluate ecosystem recovery following the implementation of nutrient management measures on land. More precisely, advice is requested to:

1. Validate the use of dissolved oxygen to characterize the trophic status of shallow estuaries of the Northumberland Strait.

- High frequency dissolved oxygen data were parsed into a combination variable of both low and high dissolved oxygen, which we termed "Eutrophic Time", defined as the frequency of time an estuary spends at dissolved oxygen concentrations above 10 mg/L or below 4 mg/L. "Eutrophic Time" was ultimately best at discriminating between estuaries according to multivariate analysis (Figure 2), was sufficient to accurately predict habitat type (eelgrass or *Ulva* spp.) (Figure 3), and was well-correlated with the stressor of interest, nitrate-N loading (as well as Water Residence Time) (Figure 4).

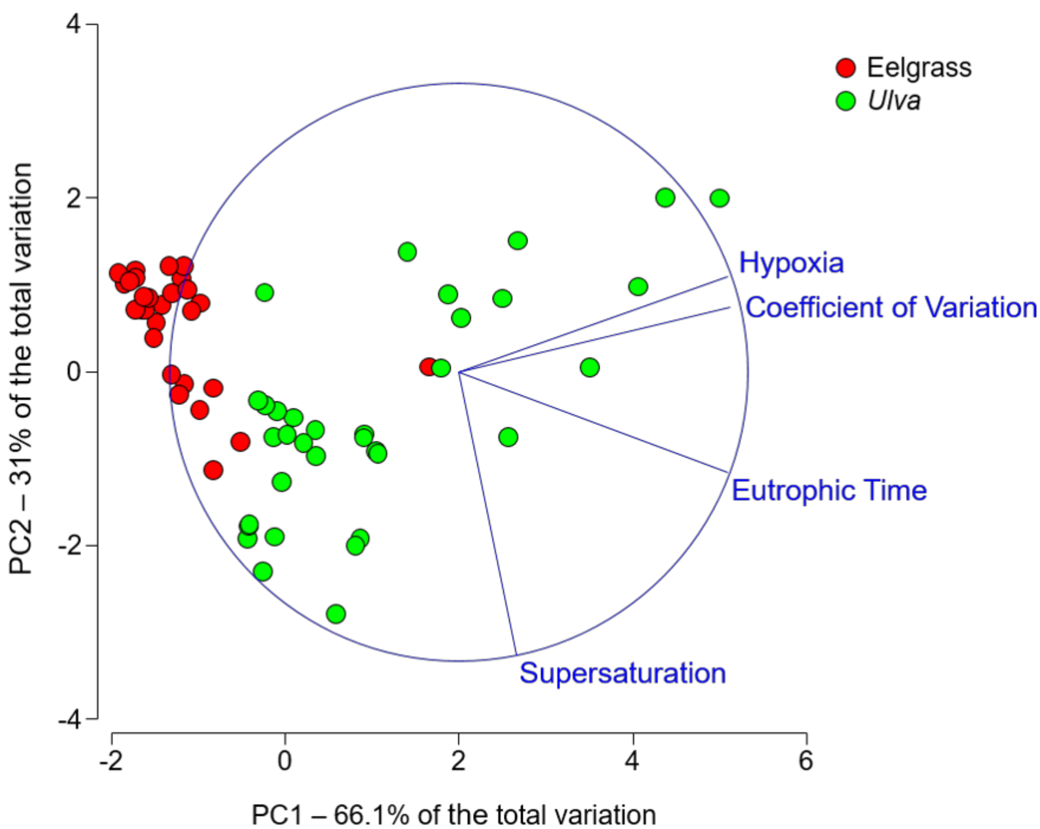

Figure 2. Principal Component Analysis using the strongest dissolved oxygen correlates identified in Coffin et al. 2018. Overall, 97% of the total variation is explained by the first two axes, 66.1% and 31% respectively. Sites are indicated by dominant vegetation with Z. marina *dominated estuaries indicated by red circles and* Ulva *spp. dominated estuaries by green circles.*

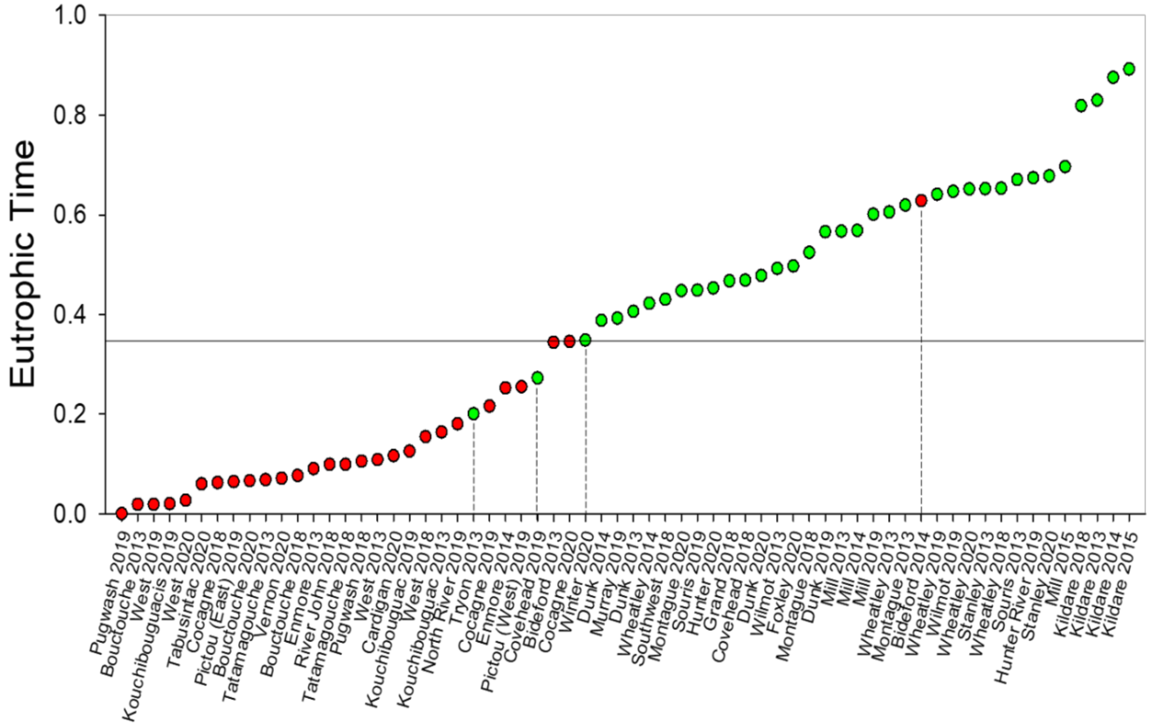

Figure 3. Eutrophic time at each site for each year sampled. Sites are presented in ascending order for Eutrophic Time and are coloured according to dominant vegetation with Z. marina *dominated estuaries indicated by red and* Ulva *spp. dominated estuaries by green. The domination vegetation shift (horizontal line) threshold is at approximately 0.35. Of note, the outlier systems Bideford 2014, an eelgrass (*Z. marina*) site grouped with* Ulva *spp. sites and Tryon 2013 and Covehead 2019,* Ulva *spp. sites grouped with eelgrass sites.*

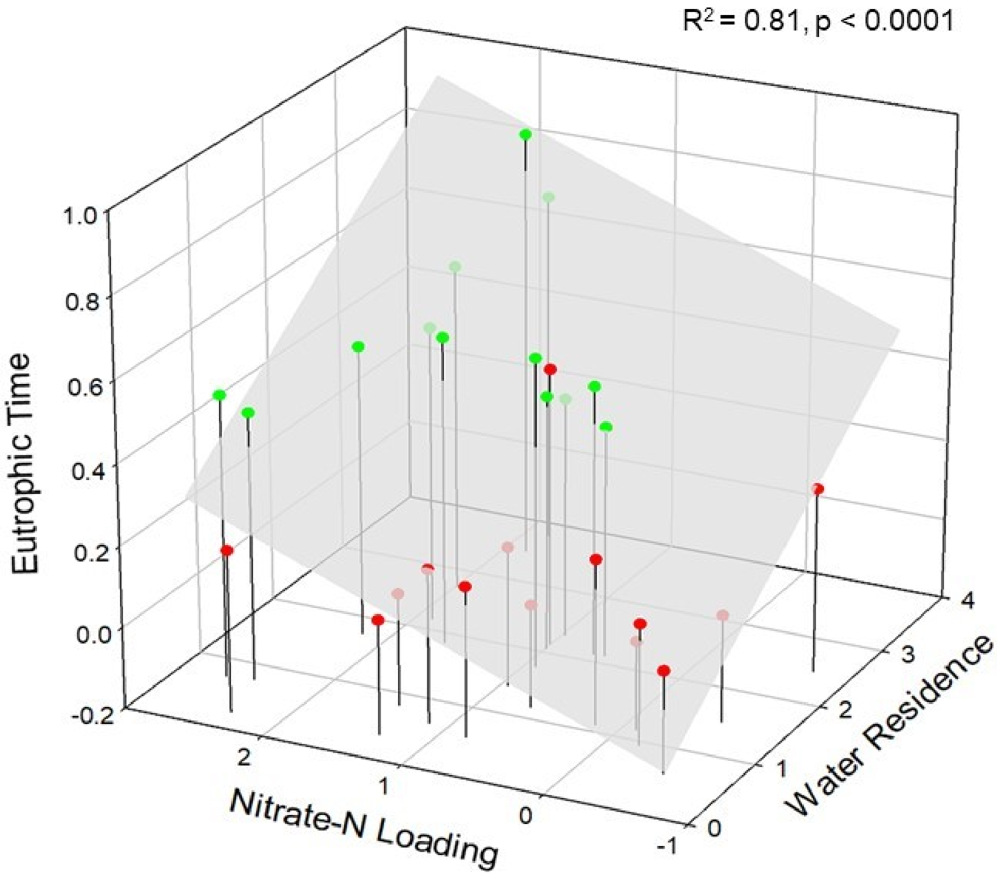

Figure 4. Representation of the planar regression for the effect of Water Residence Time and nitrate-N Loading (log-transformed) on Eutrophic time (proportion of time under 4 mg/L and over 10 mg/L). The plane is a visual representation of the best-fit regression, with the proportion of variation explained (R^2), and the significance level (p) noted. Estuaries dominated by Ulva *spp. are denoted by green circles, and* Z. marina *by red circles. Note that the best-fit plane is transparent and that points above the plane are underestimated by the model and those below are overestimated.*

2. Define conditions under which this indicator can effectively assess the trophic status of estuaries, i.e. is it applicable in other regions of Canada or specific to the environmental conditions found in estuaries of the Northumberland Strait?;

- This monitoring indicator was tested in shallow estuaries of the sGSL with both benthic (*Ulva* spp. and eelgrass) and pelagic (phytoplankton) primary production. Measured dissolved oxygen represents the balance between oxygen production via photosynthesis, consumption via respiration (including decomposition) and import and export via tidal circulation. Study systems ranged in watershed size from (17 to 386 km^2) which represents a difference of more than an order of magnitude. While we believe that the theory behind using dissolved oxygen as an indicator is universally applicable to other coastal systems, the specific dissolved oxygen thresholds and sources of nutrients are region-specific.

3. Recommend a dissolved oxygen threshold to be included in the Gulf's MEQ measure. This threshold should reflect when conditions change from those characteristics of oligotrophic to eutrophic habitat. The purpose of this threshold is to provide a target dissolved oxygen metric to manage towards that would theoretically minimize adverse effects of eutrophication such as loss of eelgrass, losses of biodiversity and abnormal dissolved oxygen signatures in estuaries. The dissolved oxygen threshold may be defined as a range rather than a specific value given that new data are being incorporated into the model developed by Coffin *et al*. (2018).

- The "Eutrophic Time" time threshold identified (0.35) effectively distinguished sites where the upper estuary was dominated by eelgrass (<0.35) compared to those where the upper estuary *Ulva* dominated habitats (>0.35; Figure 3). The implication from this study is that dissolved oxygen is site-specific and sensitive to changes in nitrate-N loading.
- While we defined this threshold based on observed data, only 3 of 64 time series were mischaracterized using the threshold of "Eutrophic Time" at 0.35 (Figure 3). As such, this threshold appears to be well-suited at predicting the dominant submerged aquatic vegetation and provides a reasonable endpoint to manage towards.

4. Based on the threshold recommended, identify first whether a management strategy is needed to reduce nitrate-N loading to the estuary and second, to estimate the degree of reduction required to remediate eutrophic estuaries.

- Our "Eutrophic Time", nitrate-N loading and Water Residence Time model predicts that, for estuaries with a "Eutrophic Time" exceeding the threshold of 0.35, a reduction in nitrate-N loading would lead to an improvement in water quality and eventually a habitat shift from *Ulva* spp. to eelgrass (see Table 1). However, our model is not mechanistic for recovery and only represents a reference condition under which we would expect a change in water quality.

*Table 1. Summary table of estuaries included in this study. Dominant vegetation is indicated by the letters Z or U to represent eelgrass (*Zostera marina*) or* Ulva *spp. habitat, respectively. See methods for calculations for Eutrophic Time, Water Residence Time and nitrate-N (kg/ha/yr). Nitrate-N target is the theoretical reduction in nitrate-N loading to shift from* Ulva *spp to eelgrass habitat, % nitrate-N change is this reduction in percent. Note that Covehead and Hunter River (highlighted in gray) both have Eutrophic Times above the 0.35 threshold but the predicted Eutrophic Time is underestimated by the model and therefore no nitrate-N target is calculated.*

Site	Watershed area (km^2)	Dominant Vegetation	Eutrophic Time	Water Residence	Nitrate-N kg/ha/yr	Nitrate-N target	% nitrate-N Change
New Brunswick							
Bouctouche	376.7	Z	0.05	1.17	4.61	-	-
Cocagne	248.8	Z	0.21	1.10	1.48	-	-
Kouchibouguac	385.7	Z	0.15	1.41	8.88	-	-
Kouchibouguacis	330.5	Z	0.02	1.14	0.80	-	-
Tabusintac*	-	Z	0.06	-	-	-	-
Nova Scotia							
Pictou East	186.6	Z	0.07	1.50	0.29	-	-
Pictou West	170.8	Z	0.26	2.50	0.19	-	-
Pugwash	112	Z	0.05	0.61	0.29	-	-
River John	274.3	Z	0.10	0.94	0.61	-	-
Tatamagouche	225.6	Z	0.08	0.35	21.67	-	-
Prince Edward Island							
Bideford	19.3	Z	0.49	2.13	10.01	2.84	72
Cardigan*	-	Z	0.12	-	-	-	-
Covehead	33.3	U	**0.37**	2.12	3.94	-	-
Dunk	161.1	U	0.46	0.77	296.87	199.75	33
Enmore	36.6	Z	0.17	0.56	6.65	-	-
Foxley*	-	U	0.50	-	-	-	-
Grand River	79.6	U	0.47	2.11	4.71	3.02	36
Hunter River	62.4	U	**0.56**	1.76	8.37	-	-
Kildare	17.4	U	0.85	3.48	70.33	0.04	99
Mill	88.3	U	0.61	2.72	96.73	0.45	99
Montague	163.8	U	0.53	2.16	76.91	2.59	99
Murray	57.3	U	0.39	2.31	9.51	1.62	83
North River	65	Z	0.18	0.65	13.66	-	-
Souris	31.6	U	0.56	1.85	42.96	6.82	84
Southwest	19	U	0.43	2.05	9.66	3.65	62
Stanley	39.2	U	0.67	3.80	67.88	0.02	99
Tryon	41.9	U	0.20	0.24	226.14	-	-
Vernon*	-	Z	0.07	-	-	-	-
West	113.6	Z	0.08	0.82	27.40	-	-
Wheatley	42.1	U	0.52	1.74	154.11	9.61	94
Wilmot	71.6	U	0.50	0.73	451.50	226.37	50
Winter*	-	U	0.35	-	-	-	-

* Dissolved oxygen data are available but not bathymetric or flow data

5. Recommend a monitoring cycle for dissolved oxygen to effectively assess the trophic status of estuaries and evaluate ecosystem recovery following the implementation of management measures on land.

- Although we developed a target “Eutrophic Time” of 0.35 to be attained through reducing nitrate-N loading, it is not possible to estimate the length of time it would take for recovery to occur using our methods. Given that nitrate-N loading isn’t expected to change dramatically in the near-term and that ecosystem changes are also expected to take time, it is not possible to predict recovery rate. The current monitoring cycle, which employs a 3-year rotation among ≈45 estuaries throughout the sGSL, should be sufficient for detecting changes in water quality. However, no scientifically-validated monitoring cycle can be recommended based on existing data and/or our understanding of recovery.

Objective 2: Advice is also requested to assess the relationship between estuarine eelgrass coverage and nutrient loading. This information is requested to determine if nutrients can be considered among the main pressures on this Ecologically Significant Species in the Gulf Region. The intent is to monitor estuarine eelgrass coverage as part of a regional monitoring program to understand the impacts of eutrophication on this valued ecosystem component and inform ecosystem recovery following the implementation of nutrient management measures on land.

1. Validate the use of eelgrass coverage as an indicator of nutrient loading to shallow estuaries of the Northumberland Strait, and evaluate the modeled relationship between eelgrass coverage and nitrogen loading established in van den Heuvel et al. (2019).

- Eelgrass coverage was well-correlated with nitrate-N loading (53% of the variation in eelgrass coverage is explained; Figures 5,6). While the relationship between eelgrass coverage and nitrate-N loading is strong, eelgrass is also sensitive to a variety of other stressors other than nutrients (temperature, invasive species, sediments, etc.). This means that changes to eelgrass aren’t necessarily a reflection of nutrient impact.

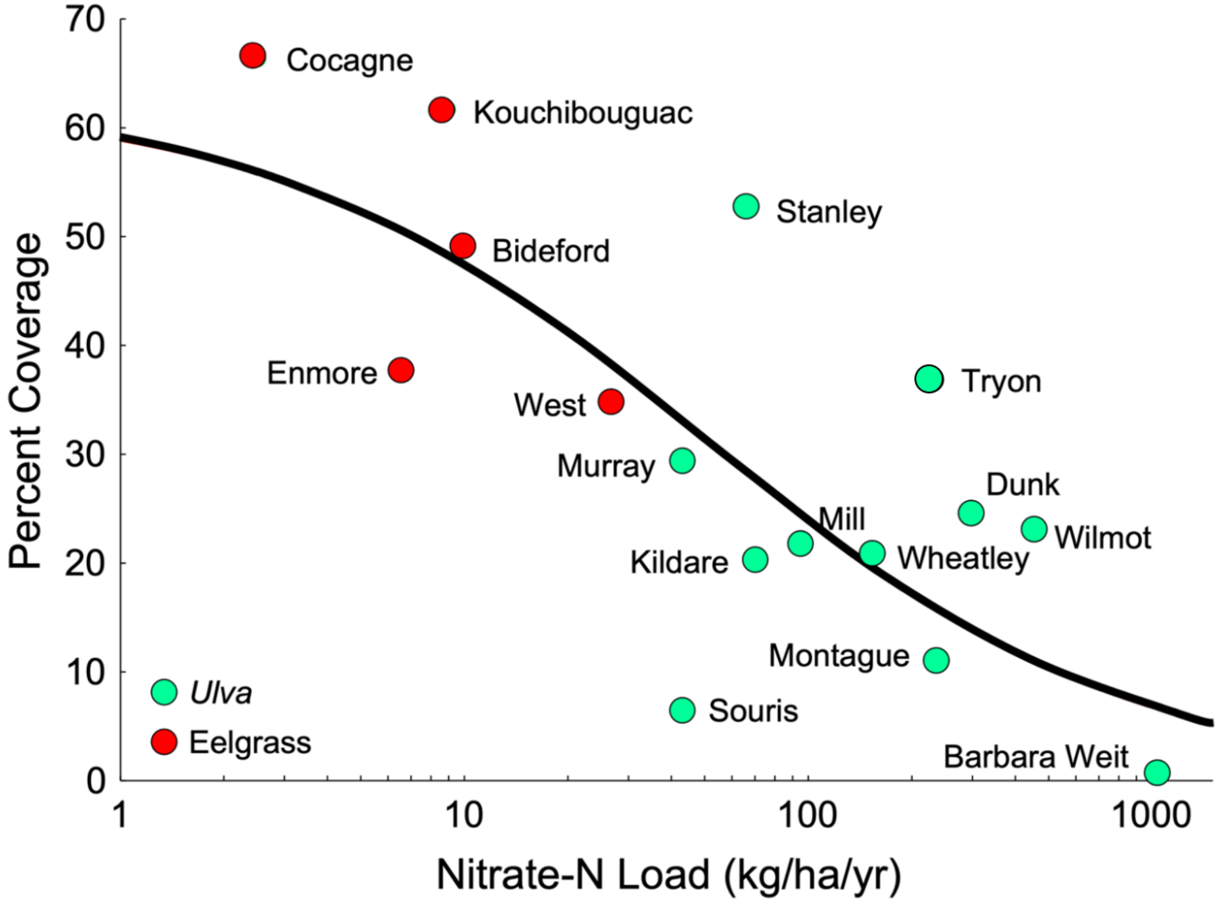

Figure 5. Logistic regression between the percent coverage of eelgrass and nitrate-N loading (log scale) across sites in PEI and NB. Eelgrass coverage data were collected in 2014, except for Barbara Weit, which was measured in 2018. Green circles denote sites that are dominated by Ulva *spp. in the upper estuary, whereas red points denote sites that are dominated by eelgrass (*Z. marina*) in the upper estuary. The black line represents the logistic regression line of best fit.*

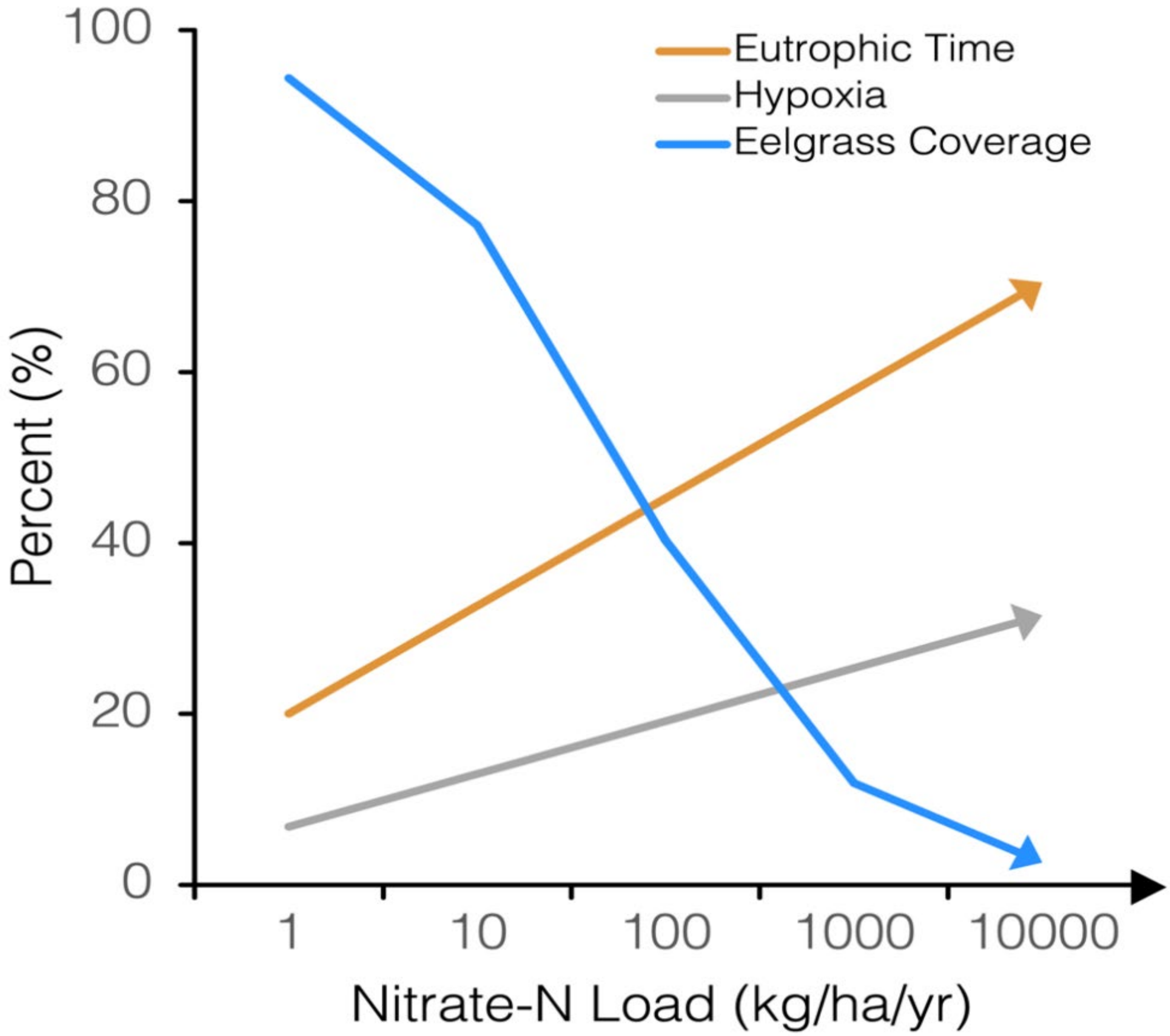

Figure 6. Theoretical relationship between changes in Eutrophic Time, Hypoxia (dissolved oxygen) and Eelgrass Coverage for a hypothetical estuary (computed using the average Water Residence Time among all sites) and log-scale ascending nitrate-N loading. Note that eelgrass coverage and the metrics representing symptoms of eutrophication are inversely correlated.

2. Define conditions under which this indicator is effective, i.e. is it applicable in other regions of Canada or specific to the environmental conditions found in estuaries of the Northumberland Strait?;

- Eelgrass coverage monitoring is already used worldwide as an indicator of ecosystem health, including impacts from nutrients. The novelty of this research was the introduction of a “potential habitat” layer where eelgrass could theoretically occupy, herein defined by salinity and mean water depth, through which to compare estuaries. It is not unreasonable to think that this approach would be applicable for shallow estuaries of the North Atlantic, though what qualifies as potential habitat should reflect conditions under which eelgrass thrives in that specific region.

Sources of Uncertainty

The monitoring indicator presented here was devised for assessing nutrient impacts for the sGSL, and represents an improvement on previous versions, as 81% of the overall variation between estuaries was accounted for using a simple dissolved oxygen metric, Eutrophic Time. Furthermore, the relatively strong relationship between nitrate-N loading and eelgrass coverage, the biological indicator of interest, is also encouraging. Despite this success, the researchers associated with this project recognize the limitations of the work and are currently attempting to refine the predictor variables (i.e. nitrate-N loading and Water Residence Time).

Dissolved oxygen loggers were deployed in the 10% area of the estuary, as defined by a salinity range of 15-25 PSU. This area was selected because it is where nitrogen is first available for marine plants and where nutrient uptake is theoretically highest (Valiela et al. 1997). This theory can be corroborated through observation as this is the area where anoxia typically occurs in nutrient impacted estuaries. Nevertheless, there is some ambiguity as to monitoring site selection. To resolve this issue, dissolved oxygen monitoring was conducted at multiple locations throughout a single entire estuary to compare dissolved oxygen spatially. Loggers were deployed at 5% intervals from brackish water (1% area) to marine water where the estuary joins the adjoining bay (100% area). These data have yet to be published but provide preliminary support that dissolved oxygen profiles from the 5-35% area are comparable. What this means from a monitoring perspective is that there is a relatively large area to deploy the dissolved oxygen logger and still acquire representative data for that watershed/estuary. Together, this means that the existing methodology is probably robust and helps to explain why we observed such strong correlation between dissolved oxygen and our predictor variables at the estuary scale. However, the applicability of these findings to other estuaries remains uncertain.

This model is driven using only external nutrient inputs and Water Residence Time. However, it is quite likely that internal nutrient availability also contributes to the dissolved oxygen values observed in this study and is perhaps even dominant. Eventually, nutrient loading in our region should include both internal and external components, as has been calculated for other systems (Valdemarsen et al. 2015). Once these parameters are better understood, predictions on how systems will respond to reductions in external nutrient loading may improve and provide more detailed advice to MEQ in the future.

This model is driven by a single nutrient (nitrogen). However, other nutrients (e.g. phosphorous, silica, carbon) contribute to primary production and may be limiting at different times and in different areas of an estuary. Including the input of these nutrients in subsequent models may improve model performance.

In this study, a tidal prism model was used to calculate Water Residence Time. While the output of that equation yielded results that functioned well in our model, it is clear that more accurate methodology would be of benefit. To this end, the authors of this report are helping to develop a regional hydrodynamic model that would provide more accurate estimates for water renewal time within the upper portion of sGSL estuaries. Such a model could be exploited to better track nutrients throughout a given estuary and identify zones outside of the upper estuary that may be at risk of nutrient impacts.

The indicator (dissolved oxygen) and general principles behind the model assessed in this study are universally applicable to other systems. However, the predictor variables of the model would need to be tailored for other regions. Thus, the specific parameters of our model are, at present, only useful for assessing the trophic status of sGSL estuaries.

CONCLUSIONS AND ADVICE

The models used in this study provide a useful tool for identifying trophic status for southern Gulf of St. Lawrence (sGSL) estuaries, there is room to improve the relationship between predictor variables and dissolved oxygen/eelgrass coverage. While continued refinement of the dissolved oxygen model is possible, these refinements would not be expected to affect decision-making given that the model contained herein already identifies estuaries requiring nitrogen reduction from those that do not. Ultimately, such a decision regarding the usefulness of model refinement will be dictated by whether more detailed information is needed to advise further iterations of the Marine Environmental Quality (MEQ) measure. Dissolved oxygen and eelgrass monitoring are complementary tools that provide a comprehensive assessment of the trophic status of estuaries in the sGSL. While eelgrass is an Ecologically Significant Species and its distribution is impacted by nutrients, high-frequency dissolved oxygen monitoring is a more useful tool than eelgrass coverage for assessing nutrient impacts in the sGSL.

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SOURCES OF INFORMATION

This Science Advisory Report is from the Regional Advisory Meeting of February 23-24, 2021 on the Validation of DO as MEQ measure of nutrient loading status of estuaries. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

Bugden, G., Jiang, Y., van den Heuvel, M., Vandermeulen, H., MacQuarrie, K., Crane, C., and Raymond, B., 2014. Nitrogen loading criteria for estuaries in Prince Edward Island Canadian Technical Report of Fisheries and Aquatic Sciences 3066, vii + 43 p.

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