*Land Economics* 96(4), November 2020

"Including Additional Pollutants into an Integrated Assessment Model for Estimating Nonmarket Benefits from Water Quality" by Robert Griffin, Adrian Vogl, Stacie Wolny, Stefanie Covino, Eivy Monroy, Heidi Ricci, Richard Sharp, Courtney Schmidt, and Emi Uchida

# APPENDIX

| Contaminant | Units | Raw Value | Subindex Value |
|---|---|---|---|
| Dissolved Oxygen (DO) | mg/L | DO ≤ 3.3 | 10 |
| | | 3.3 < DO < 10.5 | $-80.29 + 31.88*DO - 1.401*DO^2$ |
| | | 10.5 ≤ DO | 100 |
| Enterococcus (E) | cfu/100mL | E ≤ 50 | 98 |
| | | 50 < E ≤ 1600 | 98 * exp(-0.00099178*(E - 50)) |
| | | 1600 < E | 10 |
| Total Nitrogen (TN) | mg/L | TN ≤ 3 | 100 * exp(-0.4605*TN) |
| | | 3 < TN | 10 |
| Total Phosphorus (TP) | mg/L | TP ≤ 0.25 | $100 - 299.5*TP - 0.1384*TP^2$ |
| | | 0.25 < TP | 10 |
| Total Suspended Solids (TSS) | mg/L | TSS ≤ 28 | 100 |
| | | 28 < TSS ≤ 168 | 158.48 * exp(-0.0164*TSS) |
| | | 168 < TSS | 10 |
| Chlorophyll *a* (ChA) | µg/L | ChA ≤ 40 | 100 * exp(-0.05605*ChA) |
| | | 40 < ChA | 10 |

From (EPA, 2009; EPA, 2015), substituting enterococcus for fecal coliform. TSS, TN, and TP functional forms employ parameters derived specifically for the "Northeastern Coastal Zone" EPA ecoregion (appendix G, EPA, 2015).

Table A1 – Subindex transformation curves

| | **2001** | | **2011** | |
|---|---|---|---|---|
| **Loads (metric tons)** | **Zone 1** | **Zone 2** | **Zone 1** | **Zone 2** |
| *Non-point* | | | | |
| Total Nitrogen | 1574 | 124 | 1592 | 125 |
| Total Phosphorus | 51.4 | 4.5 | 51.9 | 4.6 |
| Sediment | 41093 | 12672 | 45636 | 13052 |
| *Point* | | | | |
| Total Nitrogen | 4879 | 271 | 2131 | 162 |
| Total Phosphorus | 433.2 | 43.5 | 274.7 | 44.5 |
| *Point + Non-point* | | | | |
| Total Nitrogen | 6454 | 394 | 3723 | 287 |
| Total Phosphorus | 485 | 48 | 327 | 49 |
| Sediment | 41093 | 12672 | 45636 | 13052 |

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Table A2 – Estimated annual load of total nitrogen, total phosphorus, and sediment into zones 1 and 2 in Narragansett Bay for 2001 and 2011 from point and nonpoint sources. WWTF loading from Table 8.4 in (NBEP, 2017), corresponding to annual average estimates for 2000 - 2004 from (Nixon et al., 2008) and 2013 – 2015 from (NBEP, 2017).

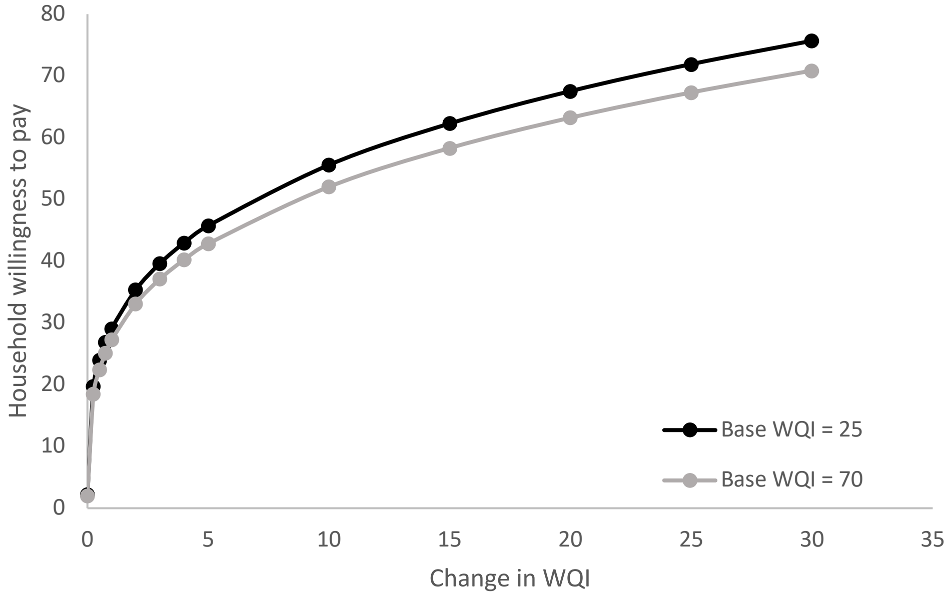

Figure A1 – Benefit transfer function. WQI values are simulated, otherwise all parameters are as noted for the 2011 time period.

*Benefit transfer function parameters*

We employ "unrestricted model two" from (Johnston et al., 2017) for use as the predictive meta-regression benefit transfer function in this study; see that study for more details on the derivation of this model. The scenario values for our retrospective analysis are given in Table A3. All of the values for variables above the zig-zag line are specific to the relevant scenario outputs of the policy site in Narragansett Bay; values for variables below that line are set at the mean value for the study sites used in the meta-analysis. Household income was gathered from the 2010 U.S. Census for municipalities that intersect the Narragansett Bay watershed and deflated using the U.S. consumer price index (CPI) to 2007 USD for use in the transfer function. Simulated willingness to pay values using the transfer function were then inflated to 2011 USD using the U.S. consumer price index.

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| Variable | BT Model Coefficient | NB Zone 1 Values | NB Zone 2 Values | Description |
|---|---|---|---|---|
| *Ln_BaseQuality* | -0.064<br>*-0.123* | 4.0 | 4.2 | Natural log of the baseline (status quo) water quality from which improvements would occur, specified on the 100-point water quality index |
| *Ln_QualityChg* | 0.281***<br>*0.106* | 2.9 | 1.7 | Natural log of the change in mean water quality valued by the study, specified on the 100-point water quality index |
| *Ln_Income* | 0.628*<br>*0.375* | 11.0 | 11.0 | Natural log of median household income (in 2007 $USD) for the market area |
| *Ln_PropAgLand* | -0.351***<br>*0.095* | -3.5 | -3.7 | Natural log of the proportion of the improved resource area (all adjacent counties) that is agricultural based on the NLCD |
| *Ln_RelativeSize* | 0.052<br>*0.019* | -2.2 | -2.3 | The natural log of the size of the market area (in square km) divided by the total area of all counties that intersect the improved water resource(s) |
| *Ln_StudyYear* | -0.478***<br>*0.080* | 3.4 | 3.4 | Natural log of the year in which the study was conducted (converted to an index by subtracting 1980, before making the log transformation) |
| *ProportionChg* | 0.525***<br>*0.189* | 0.52 | 0.48 | The shoreline length of the water body as a proportion of all analogous (e.g., coastal) shoreline lengths within affected states |
| *Voluntary* | -1.296***<br>*0.209* | 0 | 0 | Indicator that WTP was estimated using a payment vehicle described as voluntary (0 = binding and mandatory payment vehicle) |
| *OutlierBids* | -0.429***<br>*0.120* | 0 | 0 | Indicator that outlier bids were excluded when estimating WTP (0 = study excludes outlier bids) |
| *Non_Users* | -0.455***<br>*0.121* | 0 | 0 | Indicator that the survey was implemented over a population of nonusers (0 = a survey of any population that includes users) |
| *Swim_Use* | -0.391*<br>*0.220* | 1 | 1 | Indicator for survey where swimming uses are specifically noted (0 = survey does not describe effects on swimming) |

| | | | | |
|---|---|---|---|---|
| *Boat_Use* | -0.314*<br>*0.183* | 1 | 1 | Indicator for survey where boating uses are specifically noted (0 = survey does not describe effects on boating) |
| *Game_Fish* | 0.303<br>*-0.207* | 1 | 1 | Indicator for survey where game fishing uses are specifically noted (0 = survey does not describe effects on game fishing) |
| *River* | -0.226*<br>*0.128* | 0 | 0 | Indicator for whether the studied system includes rivers (0 = no) |
| *Multi_Body* | -0.525***<br>*0.145* | 0 | 0 | Indicator for whether the studied system includes multiple water body types, e.g., lakes and rivers (0 = no) |
| *Northeast_US* | 0.549**<br>*0.249* | 1 | 1 | Indicator for whether the survey included respondents from the USDA Northeast region (0 = no) |
| *MedianWTP* | -0.264<br>*-0.239* | 0 | 0 | Indicator for whether the study's WTP measure is the median (0 = mean WTP) |
| *LumpSum* | 0.727***<br>*0.136* | 0 | 0 | Indicator for whether survey asked about a lump sum payment or annual payment (0 = payments on an annual basis over more than 5 years) |
| *ChoiceExp* | 0.487**<br>*0.210* | 0.11 | 0.11 | Indicator for choice experiment survey (0 = any non-choice experiment method) |
| *Thesis* | 0.557**<br>*0.195* | 0.11 | 0.11 | Indicator for studies developed as thesis projects or dissertations (0 = study not developed as theses) |
| *NonParametric* | -0.477***<br>*0.126* | 0.43 | 0.43 | Indicator for whether WTP was estimated using non-parametric methods (0 = study used parametric methods) |
| *NonReviewed* | -0.679***<br>*0.171* | 0.24 | 0.24 | Indicator for whether the study was not published in a peer-reviewed journal (0 = study published in peer reviewed journal) |
| *Intercept* | -2.281<br>*-4.225* | | | |
| $R^2$ | 0.63 | | | |
| $\sigma_\varepsilon$ | 0.541 | | | |

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$

Table A3 – Benefit transfer parameters for comparison of water quality change in zones 1 and 2 from 2001 to 2011 (descriptions adapted from Johnston et al., 2017), standard error in italics.

### *Sediment modeling*

The Sediment Delivery Ratio (SDR) model estimates the amount of soil that is eroded from a landscape using the Universal Soil Loss Equation (USLE), and the amount of this erosion that makes it to a stream based on the Sediment Delivery Ratio method (Hamel et al., 2017). The main outputs are sediment export (with units of tons/year), representing average annual sediment delivery to streams, and maps showing per-pixel contribution to sediment export to streams. SDR requires the following inputs:

- Land use/land cover: Used to indicate erosion and conservation practice potential per land cover type
- Digital elevation model (DEM): Used to generate the stream network and trace the path of sediment as it travels downslope to a stream
- Rainfall erosivity: A measure of the intensity of rainfall, such that harder rainfall is more likely to cause soil to detach and become erosion
- Soil erodibility: A soil property that indicates how easily different types of soil detach and become erosion
- Threshold flow accumulation: An integer value indicating the amount of upstream area that must flow into a pixel before it is considered part of a stream, used with the DEM to generate a stream map
- USLE crop (C) and practice (P) coefficients, based on each land use/land cover type

| **Description** | **Source(s)** |
|---|---|
| Land use/ land cover | NLCD 2001 and 2011 https://www.mrlc.gov/data |
| Elevation (DEM; m) | USGS 1/3 arc second (~10m) NED DEM https://viewer.nationalmap.gov/ |
| Rainfall erosivity | Calculated from PRISM "normal" annual precipitation data http://www.prism.oregonstate.edu/normals/ |
| Threshold flow accumulation$^+$ | Used to define streams as closely as possible to the National Hydrography Dataset (NHD) stream line data |
| Soil erodibility | Derived from STATSGO2 using USDA Soil Data Viewer |
| USLE C factor | NRCS Rhode Island and New York Field Office Technical Guides (FOTG); (Wischmeier & Smith, 1978); Atkins 2013; Ohio EPA 2011; see Table A7 for calibrated parameters by LULC |
| USLE P factor | P = 1 for all land cover types; assumes no sediment management practices. |

$^+$ Threshold flow accumulation is an integer value indicating the amount of upstream area that must flow into a pixel before it is considered by the model to be part of a stream, and is used with the DEM to generate a stream map.

Table A4. Summary of data requirements and sources for the SDR model to estimate sediment export.

Default values for parameters specific to land use and land cover -- including the USLE C and P factors, were assigned based on a review of relevant literature from the region (NRCS Rhode Island and New York Field Office Technical Guides; Wischmeier and Smith 1978; Ohio EPA 2011; Atkins 2013; see Table A4). We did not have any information on erosion management practices related to croplands, so all P values were set equal to 1 (default value). The primary model output is a raster of sediment exported to streams, with units of tons/year/pixel. The model stops calculations when sediment moving downslope hits a stream, and assumes that this export makes it to the point of analysis downstream within a year. No in-stream processes are included. Further, the sediment model does not distinguish between erosion or sediment retention potential in areas served by WWTF and those outside these service areas.

The SDR model was run with land cover, land use-specific USLE factors, climate (rainfall erosivity) and soil characteristics (erodibility) to produce spatially-distributed estimates of non-point source sediment loading from the landscape. These total nonpoint source loadings were then adjusted to account for the retention of sediment by dams, as described below under *Dam Modeling*. The result of the dam model is a retention factor for all pixels in the Narragansett Bay watershed that was applied as a scalar to modify the per-pixel sediment export results from the SDR model. This results allows for examination of the spatial distribution of sediment loads across the watershed, by assigning each pixel a value of its net export to the bay, considering the retention effects of both intervening land cover and downstream impoundments.

The result of the above steps is a raster of net export of sediment to the Narragansett Bay watershed. The pixel-level export values were summed for each watershed zone to arrive at mean annual nonpoint source sediment loading to the bay. No point source adjustments were made to the total sediment loads. We therefore used the sediment export raster, after adjusting for retention by dams, as the basis for model calibration.

For calibration, data on sediment concentrations (ppm) and flows (cfs) were obtained for USGS gauge 01113895 (Blackstone River at Roosevelt St at Pawtucket RI), from February 2007 to March 2016. Other gauges in the study area had sediment data, but the records had large gaps and/or had been collected prior to 2002, making calibration to our 2011 modeled loads problematic. The Blackstone River gauge also had several missing records, which were filled using the LOADEST program from USGS (Runkel et al., 2004). LOADEST takes matched observations of daily sediment and flow, as well as flow data for all days in the time series, and estimates sediment loading across the time series, using a regression equation to fill in sediment values on the days where there is flow data but no observed sediment. The program selects the best fit from nine candidate models, and provides a time series of daily sediment loads (kg/day) from February 2007 to December 2016. The selected model and parameters are:

$$\ln(load) = a_0 + a_1 \ln(Q) + a_2 \ln(Q^2) + a_3 \sin(2\pi dtime) + a_4 \cos(2\pi dtime) + a_5 dtime + a_6 dtime^2$$

where:

load = constituent load (kg $d^{-1}$)

Ln(Q) = Ln(Q) - center of Ln(Q)
dtime = decimal time - center of decimal time

| Coeff. | Estimate |
|---|---|
| $a_0$ | 9.3366***<br>*0.0923* |
| $a_1$ | 1.3424***<br>*0.0845* |
| $a_2$ | 0.1920***<br>*0.0530* |
| $a_3$ | -0.3960***<br>*0.0835* |
| $a_4$ | 0.2068**<br>*0.1027* |
| $a_5$ | -0.0303<br>*0.0222* |
| $a_6$ | -0.0163*<br>*0.0092* |
| $R^2$ | 0.80 |

Adjusted maximum likelihood estimation, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$, standard deviation in italics

Table. A5. Regression results of selected LOADEST model

The daily sediment loads were summed by year and averaged to obtain the mean annual sediment load for the Blackstone River. This value was compared to the adjusted sediment load from the SDR model (after accounting for retention by dams). Global model parameters as well as LULC-based parameters were modified (Table A6) until a good fit was obtained between the modeled and estimated loads. The resulting model underestimated annual average sediment loads by 14.6%. Calibrated parameters by land use class are given below in Table A7.

| Parameter | Description | Default value | Min | Max | Increment | Calibrated value |
|---|---|---|---|---|---|---|
| Kb | Borselli K | 2 | 0.5 | 3.5 | 0.5 | 3 |
| TFA | Threshold flow accumulation | 2000 | 1000 | 3000 | 200 | 1400 |
| $IC_0$ | Determine the shape of the relationship between hydrologic connectivity and the sediment delivery ratio | 0.5 | 0.1 | 1 | 0.1 | 0.5 |
| USLE_C | Cover-management factor used in calculating erosion | by LULC (Table A7) | 0.5x | 2x (max=1) | 0.25 | by LULC (Table A7) |

Table A6. SDR model parameters, default values and ranges used for calibration.

| | USLC_C | | USLE_P | |
|---|---|---|---|---|
| LULC class | Baseline | Calibrated | Baseline | Calibrated |
| Open Water | 0 | 0 | 1 | 1 |
| Developed, Open space | 0.026 | 0.026 | 1 | 1 |
| Developed, Low Intensity | 0.018 | 0.018 | 1 | 1 |
| Developed, Medium Intensity | 0.01 | 0.01 | 1 | 1 |
| Developed, High Intensity | 0.002 | 0.002 | 1 | 1 |
| Barren Land | 0.9 | 0.9 | 1 | 1 |
| Deciduous Forest | 0.006 | 0.006 | 1 | 1 |
| Evergreen Forest | 0.006 | 0.006 | 1 | 1 |
| Mixed Forest | 0.006 | 0.006 | 1 | 1 |

| | | | | |
|---|---|---|---|---|
| Shrub/Scrub | 0.12 | 0.12 | 1 | 1 |
| Grassland/Herbaceous | 0.056 | 0.056 | 1 | 1 |
| Pasture/Hay | 0.056 | 0.056 | 1 | 1 |
| Cultivated Crops | 0.333 | 0.333 | 1 | 1 |
| Woody Wetlands | 0.013 | 0.013 | 1 | 1 |
| Emergent Herbaceous Wetlands | 0.013 | 0.013 | 1 | 1 |
| Open Water with WWTF | 0 | 0 | 1 | 1 |
| Developed, Open space with WWTF | 0.026 | 0.013 | 1 | 1 |
| Developed, Low Intensity with WWTF | 0.018 | 0.009 | 1 | 1 |
| Developed, Medium Intensity with WWTF | 0.01 | 0.005 | 1 | 1 |
| Developed, High Intensity with WWTF | 0.002 | 0.001 | 1 | 1 |
| Barren Land with WWTF | 0.9 | 0.45 | 1 | 1 |
| Deciduous Forest with WWTF | 0.006 | 0.003 | 1 | 1 |
| Evergreen Forest with WWTF | 0.006 | 0.003 | 1 | 1 |
| Mixed Forest with WWTF | 0.006 | 0.003 | 1 | 1 |
| Shrub/Scrub with WWTF | 0.12 | 0.06 | 1 | 1 |
| Grassland/Herbaceous with WWTF | 0.056 | 0.028 | 1 | 1 |
| Pasture/Hay with WWTF | 0.056 | 0.028 | 1 | 1 |
| Cultivated Crops with WWTF | 0.333 | 0.1665 | 1 | 1 |
| Woody Wetlands with WWTF | 0.013 | 0.0065 | 1 | 1 |
| Emergent Herbaceous Wetlands with WWTF | 0.013 | 0.0065 | 1 | 1 |

Table A7. Baseline and calibrated parameters used in the SDR model by land use/ land cover class. USLE_C refers to the “crop/vegetation and management factor” and USLE_P refers to the “support practice factor” of the universal soil loss equation used in the SDR model. All else equal, lower C factors will result in less soil erosion.

Following calibration on the Blackstone subwatershed, the calibrated parameters were applied to the SDR model for the entire study area. The full modeling framework (i.e., use SDR model to generate total sediment export then adjust for dam retention) was used to estimate total sediment loads. Finally, total loads were summed for each zone of the Narragansett Bay and converted to concentrations for use in the WQI as described in the main text.

### *Nitrogen and phosphorus modeling*

Total nitrogen (TN) and total phosphorus (TP) loads were modeled using the InVEST Nutrient Delivery Ratio (NDR) model (Sharp et al., 2016; Redhead et al., 2018). The model estimates the amount of nutrients that run off of a landscape via nutrient loading information, and the amount of this nutrient runoff that makes it to a stream based on a nutrient delivery ratio method. This method relates upslope contributing area to retention potential along the downslope flow path, similar to the sediment delivery ratio approach. Nutrient may be partitioned into sediment-bound and dissolved parts, which are transported through surface and subsurface flow, respectively, stopping when they reach a stream.

The NDR model requires spatial data on land use and land cover, land use-specific loading and retention factors, a digital elevation model (DEM), and precipitation (used as a proxy for surface runoff), and produces spatially-distributed estimates of pollutant loading from the landscape. The results from the NDR reflect the per-pixel load of TN and TP, modified by the ability of vegetation to retain nutrients as it passes over the landscape, accounting for both surface and subsurface retention. The main outputs are nutrient export (with units of kg/year), representing average annual nutrient delivery to streams, and maps showing per-pixel contribution to nutrient yield. A summary of data requirements and sources for the NDR model is given in Table A8.

| **Description** | **Source(s)** |
|---|---|
| Land use/ land cover | NLCD 2001 and 2011 https://www.mrlc.gov/data |
| Elevation (DEM; m) | USGS 1/3 arc second (~10m) NED DEM https://viewer.nationalmap.gov/ |
| Mean annual precipitation (used as runoff proxy; mm) | Calculated from PRISM "normal" annual precipitation data http://www.prism.oregonstate.edu/normals/ |
| Threshold flow accumulation[+] | 1400, used to define streams as closely as possible to the National Hydrography Dataset (NHD) stream line data |
| TN and TP load by LULC class (kg/ha/yr) | Buzzard's Bay National Estuary Program Nitrogen Management Strategies & Tools; (Blumstein & Thompson, 2015); Mass DEP (2016); EcoLogic LLC 2007; see Table A11 for calibrated parameters by LULC |
| TN and TP load from atmospheric deposition (kg/ha/yr) | Median of modelled atmospheric deposition from SPARROW New England model (Moore et al., 2011). Atmospheric deposition of P set to 0. This flux is considered negligible, as it constitutes less than 1% of the P budget (Krumholz, 2012). |
| TN and TP retention efficiency (%) | (Groffman et al., 2004; Blumstein & Thompson, 2015; Peterjohn & Correll, 1984) New York AVGWLF; see Table A11 for calibrated parameters by LULC |
| Critical length TN/TP (m) | Outside of WWTF areas = 150; within WWTF areas = 10 (Mayer et al., 2007; Zhang et al., 2010) |
| Proportion subsurface N/P (%) | Buzzard's Bay National Estuary Program Nitrogen Management Strategies & Tools; see Table A11 for calibrated parameters by LULC |
| Subsurface maximum retention efficiency (%) | Default set to lowest retention value in LULC database. |

[+] Threshold flow accumulation is an integer value indicating the amount of upstream area that must flow into a pixel before it is considered by the model to be part of a stream, and is used with the DEM to generate a stream map.

Table A8. Summary of data requirements and sources for the NDR model to estimate total nitrogen (TN) and total phosphorus (TP).

Default values for parameters specific to land use and land cover -- including total annual loads (in kg/ha/yr) and retention efficiencies (%) for TN and TP, and proportion of nutrients in subsurface flow (%) -- were assigned based on a review of relevant literature from the region (Table A9). Soil particles do not retain nitrate very well and therefore leached N has little chance to be retained (Johnson et al., 2005). Therefore the maximum subsurface retention efficiency parameter was initially set to 0.05, equal to the lowest N retention efficiency of any land use class. We assume the proportion of phosphorus in subsurface flow to be 0 for all land use types, because the potential for P loss is primarily associated with erosion and surface runoff; P leaching is typically a problem only in soils with very high P or in areas with extensive tile drainage (Hyland et al., 2005).

To account for the fact that parts of the study area are within the treatment areas for several wastewater treatment facilities (WWTF), the base NLCD land cover map for 2011 was re-classified into land covers located within and without WWTF treatment areas. Spatial coverage for WWTF treatment service areas were obtained from (NBEP, 2017). The assumptions for WWTF areas are that: (1) the land use-based loadings are the same in treated and untreated areas; (2) the retention of nutrients within WWTF service areas is modeled as 100%, based on the assumption that all runoff generated within these areas is treated and the net loading of TN and TP from these areas is included in the following step, as point-source loadings at the point of discharge from the WWTFs; (3) leached nitrogen is not treated by the WWTF, so the proportion subsurface N parameter values are the same in treated and untreated areas. Note that this method does not account for episodic loadings of nutrients that can occur during large events, in which stormwater overflows bypass the treatment facilities. We did not specifically model the impact of on-site wastewater treatment systems (OWTS) on total nutrient loads. Loads from developed land cover types outside the WWTF service areas are assumed to include loading from OWTSs.

| LULC class | Base TN load | Atmos-pheric TN load | Total TN load | Retention efficiency TN | Proportion subsurface TN | TP load | Retention efficiency TP | Proportion subsurface TP |
|---|---|---|---|---|---|---|---|---|
| Open Water | 0.001 | 6.3 | 6.301 | 0.05 | 0.66 | 0 | 0.01 | 0 |
| Developed, Open space | 0.8 | 6.3 | 7.1 | 0.5 | 0.2 | 0.1 | 0.02 | 0 |
| Developed, Low Intensity | 6.8 | 6.3 | 13.1 | 0.75 | 0.2 | 0.3 | 0.02 | 0 |
| Developed, Medium Intensity | 6 | 6.3 | 12.3 | 0.75 | 0.2 | 0.5 | 0.01 | 0 |
| Developed, High Intensity | 8.6 | 6.3 | 14.9 | 0.75 | 0.2 | 1 | 0.01 | 0 |
| Barren Land | 6 | 6.3 | 12.3 | 0.05 | 0.47 | 0.28 | 0.02 | 0 |
| Deciduous Forest | 0.45 | 6.3 | 6.75 | 0.88 | 0.47 | 0.07 | 0.05 | 0 |
| Evergreen Forest | 0.45 | 6.3 | 6.75 | 0.88 | 0.47 | 0.2 | 0.05 | 0 |
| Mixed Forest | 0.45 | 6.3 | 6.75 | 0.88 | 0.47 | 0.14 | 0.05 | 0 |
| Shrub/Scrub | 0.45 | 6.3 | 6.75 | 0.88 | 0.47 | 0.28 | 0.05 | 0 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Grassland/Herbaceous | 0.97 | 6.3 | 7.27 | 0.5 | 0.47 | 0.28 | 0.02 | 0 |
| Pasture/Hay | 0.97 | 6.3 | 7.27 | 0.5 | 1 | 0.45 | 0.02 | 0 |
| Cultivated Crops | 10.25 | 6.3 | 16.55 | 0.77 | 0.3 | 1.5 | 0.02 | 0 |
| Woody Wetlands | 2.24 | 6.3 | 8.54 | 0.12 | 0.66 | 0.4 | 0.25 | 0 |
| Emergent Herbaceous Wetlands | 5.25 | 6.3 | 11.55 | 0.12 | 0.66 | 0.3 | 0.25 | 0 |
| Open Water with WWTF | 0.001 | 6.3 | 6.301 | 1 | 0.66 | 0 | 1 | 0 |
| Developed, Open space with WWTF | 0.8 | 6.3 | 7.1 | 1 | 0.2 | 0.1 | 1 | 0 |
| Developed, Low Intensity with WWTF | 6.8 | 6.3 | 13.1 | 1 | 0.2 | 0.3 | 1 | 0 |
| Developed, Medium Intensity with WWTF | 6 | 6.3 | 12.3 | 1 | 0.2 | 0.5 | 1 | 0 |
| Developed, High Intensity with WWTF | 8.6 | 6.3 | 14.9 | 1 | 0.2 | 1 | 1 | 0 |
| Barren Land with WWTF | 6 | 6.3 | 12.3 | 1 | 0.47 | 0.28 | 1 | 0 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Deciduous Forest with WWTF | 0.45 | 6.3 | 6.75 | 1 | 0.47 | 0.07 | 1 | 0 |
| Evergreen Forest with WWTF | 0.45 | 6.3 | 6.75 | 1 | 0.47 | 0.2 | 1 | 0 |
| Mixed Forest with WWTF | 0.45 | 6.3 | 6.75 | 1 | 0.47 | 0.14 | 1 | 0 |
| Shrub/Scrub with WWTF | 0.45 | 6.3 | 6.75 | 1 | 0.47 | 0.28 | 1 | 0 |
| Grassland/Herbaceous with WWTF | 0.97 | 6.3 | 7.27 | 1 | 0.47 | 0.28 | 1 | 0 |
| Pasture/Hay with WWTF | 0.97 | 6.3 | 7.27 | 1 | 1 | 0.45 | 1 | 0 |
| Cultivated Crops with WWTF | 10.25 | 6.3 | 16.55 | 1 | 0.3 | 1.5 | 1 | 0 |
| Woody Wetlands with WWTF | 2.24 | 6.3 | 8.54 | 1 | 0.66 | 0.4 | 1 | 0 |
| Emergent Herbaceous Wetlands with WWTF | 5.25 | 6.3 | 11.55 | 1 | 0.66 | 0.3 | 1 | 0 |

Table A9. Baseline parameters used in the NDR model by land use/ land cover class

The nutrient export output from the NDR model (with units of kg/year) represents the average annual non-point source TN and TP load from the landscape. These total nonpoint source loadings were then adjusted to account for the retention of nitrogen by dams, as described below under *Dam Modeling*. The result of the dam model is a retention factor for all pixels in the Narragansett Bay watershed, which was then applied as a scalar to modify the per-pixel TN export results from the NDR model. This results allows for examination of the spatial distribution of TN loads across the watershed, by assigning each pixel a value of its net export to the bay, considering the retention effects of both intervening land cover and downstream impoundments. Retention of TP by dams was not modeled, due to the complex effect of dams on phosphorus retention, cycling, and remobilization and the fact that reservoirs may act as either a source or a sink for phosphorus. Such modeling was outside the scope of this study, so nonpoint source TP export as estimated by the NDR model was used directly.

The result of the above steps is a raster of net export of TN and TP to the Narragansett Bay watershed. The pixel-level export values were summed for each watershed zone to arrive at mean annual nonpoint source nutrient loading to the bay. Next, point source loadings of nitrogen and phosphorus contributing to each zone were added to arrive at the total load. Locations of WWTPs and their nutrient loads for 2001 and 2011 were taken from a recent nutrient budget analysis in the bay (NBEP, 2017).

We examined various sources for observed TN and TP data for calibration of the NDR model. First, all nitrogen and phosphorus concentration data were retrieved for HUCs 1090003 and 1090004 from www.waterqualitydata.us. Of these data, only 9 sites had both nutrient and flow data from the same location (required to convert concentrations to loads for calibration). Of these 9 sites, all were located downstream of point source contributions. Uncertainty in our estimates of point source contributions made these not ideal for calibrating nonpoint source loads. Second, the SPARROW model (Moore et al., 2011) estimates total nonpoint source nitrogen and phosphorus loading considering atmospheric deposition, land-based sources, and point sources. However, the landcover on which the estimates are based comes from NLCD's 1992 dataset, which was deemed inadvisable to compare directly to our model estimates stemming from 2011 land cover data.

We elected to use the (NBEP, 2017) estimates of TN and TP loads, since these were broken out into point and nonpoint source contributions (allowing for calibration of the nonpoint source loading model without added uncertainty from point source contributions) and were based on the same land cover data as used in our model (NLCD 2011). Calibration was performed for a subset of the modeled area (the Moshassuck subwatershed). We selected this subwatershed because it was the only area for which loading estimates were available which had no point source loadings, allowing direct comparison with our nonpoint source loading estimates. The watershed was delineated based on the location of USGS gauge 01114000 (Moshassuck River at Providence, RI). Model calibration focused on the total nonpoint source load from the Moshassuck watershed, obtained by summing the pixel-level outputs of TN and TP export from the InVEST NDR model, with TN adjusted for retention by dams as described above. Global model parameters as well as LULC-based parameters were modified (Table A10) until a good fit was obtained between the modeled and estimated loads from NBEP (2017). The resulting model overestimated annual average nonpoint source TN by 3.3%, and overestimated TP by 3.9%. Calibrated parameters by land use class are given below in Table A11.

| Parameter | Description | Default value | Min | Max | Increment | Calibrated value |
|---|---|---|---|---|---|---|
| Kb | Borselli K | 2 | 0.5 | 3.5 | 0.5 | 3 |
| TFA | Threshold flow accumulation | 2000 | 1000 | 3000 | 200 | 1400 |
| load_n | N load (kg/ha/yr) | by LULC (Table A9) | 0.5x | 2x | 0.25 | by LULC (Table A11) |
| load_n, atm dep | N load from atmospheric deposition (kg/ha added to load_n for ALL LULCs) | 6.3 | 2.3 | 51.3 | 1 | 12.6 |
| eff_n | N retention efficiency (%), non-WWTF classes only | by LULC (Table A9) | 0.5x | 2x (max=1) | 0.25 | by LULC (Table A11) |
| load_p | P load (kg/ha/yr), non-WWTF classes only | by LULC (Table A9) | 0.5x | 2x | 0.25 | by LULC (Table A11) |
| eff_p | P retention efficiency (%), non-WWTF classes only | by LULC (Table A9) | 0.5x | 5x (max=1) | 0.5 | by LULC (Table A11) |

| | | | | | | |
|---|---|---|---|---|---|---|
| crit_len_p and crit_len_n | Critical length for maximum retention | 150 | 100 | 1000 | 100 | 150 |
| proportion_ subsurface_n | N in subsurface flow | by LULC (Table A9) | 0.5x | 2x (max=1) | 0.25 | by LULC (Table A11) |
| proportion_ subsurface_n (WWTF) | N in subsurface flow (in WWTF areas) | by LULC (Table A9) | 0.5x | 2x (max=1) | 0.25 | by LULC (Table A11) |
| proportion_ subsurface_p | P in subsurface flow | 0 | 0 | 0.5 | 0.25 | 0 |
| proportion_ subsurface_p (WWTF) | P in subsurface flow (in WWTF areas) | 0 | 0 | 0.5 | 0.25 x | 0 |
| subsurface max retention efficiency (N) | Maximum retention efficiency (N) | 0.05 | 0.5x | 10x | 0.5 | 0.025 |
| subsurface max retention efficiency (P) | Maximum retention efficiency (P) | 0.01 | 0.01 | 10x | 0.01 | 0.025 |

Table A10. NDR model parameters, default values and ranges used for calibration.

| **LULC class** | **Base TN load** | **Atmos-pheric TN load** | **Total TN load** | **Retention efficiency TN** | **Proportion subsurface TN** | **TP load** | **Retention efficiency TP** | **Proportion subsurface TP** |
|---|---|---|---|---|---|---|---|---|
| Open Water | 0.0015 | 9.45 | 9.4515 | 0.05 | 0.66 | 0 | 0.01 | 0 |
| Developed, Open space | 1.2 | 9.45 | 10.65 | 0.5 | 0.2 | 0.2 | 0.02 | 0 |
| Developed, Low Intensity | 10.2 | 9.45 | 19.65 | 0.75 | 0.2 | 0.6 | 0.02 | 0 |
| Developed, Medium Intensity | 9 | 9.45 | 18.45 | 0.75 | 0.2 | 1 | 0.01 | 0 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Developed, High Intensity | 12.9 | 9.45 | 22.35 | 0.75 | 0.2 | 2 | 0.01 | 0 |
| Barren Land | 9 | 9.45 | 18.45 | 0.05 | 0.47 | 0.56 | 0.02 | 0 |
| Deciduous Forest | 0.675 | 9.45 | 10.125 | 0.88 | 0.47 | 0.14 | 0.05 | 0 |
| Evergreen Forest | 0.675 | 9.45 | 10.125 | 0.88 | 0.47 | 0.4 | 0.05 | 0 |
| Mixed Forest | 0.675 | 9.45 | 10.125 | 0.88 | 0.47 | 0.28 | 0.05 | 0 |
| Shrub/Scrub | 0.675 | 9.45 | 10.125 | 0.88 | 0.47 | 0.56 | 0.05 | 0 |
| Grassland/Herbaceous | 1.455 | 9.45 | 10.905 | 0.5 | 0.47 | 0.56 | 0.02 | 0 |
| Pasture/Hay | 1.455 | 9.45 | 10.905 | 0.5 | 1 | 0.9 | 0.02 | 0 |
| Cultivated Crops | 15.375 | 9.45 | 24.825 | 0.77 | 0.3 | 3 | 0.02 | 0 |
| Woody Wetlands | 3.36 | 9.45 | 12.81 | 0.12 | 0.66 | 0.8 | 0.25 | 0 |
| Emergent Herbaceous Wetlands | 7.875 | 9.45 | 17.325 | 0.12 | 0.66 | 0.6 | 0.25 | 0 |
| Open Water with WWTF | 0.0015 | 9.45 | 9.4515 | 1 | 0.66 | 0 | 0.8 | 0 |
| Developed, Open space with WWTF | 1.2 | 9.45 | 10.65 | 1 | 0.2 | 0.2 | 0.8 | 0 |
| Developed, Low Intensity with WWTF | 10.2 | 9.45 | 19.65 | 1 | 0.2 | 0.6 | 0.8 | 0 |
| Developed, Medium Intensity with WWTF | 9 | 9.45 | 18.45 | 1 | 0.2 | 1 | 0.8 | 0 |
| Developed, High Intensity with WWTF | 12.9 | 9.45 | 22.35 | 1 | 0.2 | 2 | 0.8 | 0 |
| Barren Land with WWTF | 9 | 9.45 | 18.45 | 1 | 0.47 | 0.56 | 0.8 | 0 |
| Deciduous Forest with WWTF | 0.675 | 9.45 | 10.125 | 1 | 0.47 | 0.14 | 0.8 | 0 |
| Evergreen Forest with WWTF | 0.675 | 9.45 | 10.125 | 1 | 0.47 | 0.4 | 0.8 | 0 |
| Mixed Forest with WWTF | 0.675 | 9.45 | 10.125 | 1 | 0.47 | 0.28 | 0.8 | 0 |
| Shrub/Scrub with WWTF | 0.675 | 9.45 | 10.125 | 1 | 0.47 | 0.56 | 0.8 | 0 |
| Grassland/Herbaceous with WWTF | 1.455 | 9.45 | 10.905 | 1 | 0.47 | 0.56 | 0.8 | 0 |
| Pasture/Hay with WWTF | 1.455 | 9.45 | 10.905 | 1 | 1 | 0.9 | 0.8 | 0 |
| Cultivated Crops with WWTF | 15.375 | 9.45 | 24.825 | 1 | 0.3 | 3 | 0.8 | 0 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Woody Wetlands with WWTF | 3.36 | 9.45 | 12.81 | 1 | 0.66 | 0.8 | 0.8 | 0 |
| Emergent Herbaceous Wetlands with WWTF | 7.875 | 9.45 | 17.325 | 1 | 0.66 | 0.6 | 0.8 | 0 |

Table A11. Calibrated parameters used in the NDR model by land use/ land cover class

Following calibration on the Moshassuck subwatershed, the calibrated parameters were applied to the NDR model for the entire study area. The full modeling framework (i.e., use NDR model to generate total export, adjust for dam retention of TN, and add point sources) was then used to estimate total pollutant loads. Finally, total loads were summed for each zone of the Narragansett Bay and converted to concentrations for use in the WQI as described in the main text.

### *Dissolved oxygen modeling*

Multiple studies indicate that dissolved oxygen is linked to other water quality variables and that these drivers appear to vary by location and feature non-linear relationships (Prasad et al., 2011). In Narragansett Bay, there is strong interannual variability in dissolved oxygen concentrations, a persistent north-south gradient from low to high dissolved oxygen concentration, and generally lower dissolved oxygen observed in wet years (NBEP, 2017). We establish a predictive model of dissolved oxygen by estimating it as a function of other contemporaneously sampled water quality variables at six water quality gauges in Narragansett Bay maintained by the USGS. The gauges are: Blackstone - USGS gauge 01113895, Pawtuxet - 01116500, Moshassuck - 01114000, Ten Mile - 01109403, Woonasquatucket - 01114500, and Taunton - 01109060

Available data at these gauges allow us to characterize several potential predictors of dissolved oxygen, including water temperature, freshwater discharge volume, water pH, suspended solids, nitrogen and phosphorus levels, and fecal coliform concentrations (Table A12). With this data, we specify a range of model specifications, including one emulating (Prasad et al., 2011), using site fixed effects to control for unobserved variation at each gauge station (Table A13). We generally find that nutrient levels, temperature, and freshwater discharge are significantly correlated with dissolved oxygen. Because of limited spatially representative temperature and flow data throughout the bay, we opted for model 6 that predicts dissolved oxygen as a combination of total nitrogen and total phosphorus. The predictive model is: $DO = 12.74 - 2.13TN - 12.36TP + 2.72TN * TP$. The omitted variables have opposing correlations with dissolved oxygen, so we cannot determine the direction of bias for this predictive equation.

| **Variable** | **Units** | **Obs** | **Mean** | **Std. Dev.** | **Min** | **Max** |
|---|---|---|---|---|---|---|
| Temp | Deg C | 399 | 13.3 | 8.2 | 0.0 | 29.5 |
| Discharge | ft$^3$/sec | 372 | 519 | 770 | 4 | 7650 |
| Dissolved Oxygen (DO) | mg/L | 399 | 9.1 | 3.5 | 0.6 | 17.0 |
| pH |  | 396 | 6.8 | 0.5 | 5.2 | 8.6 |
| Total Suspended Solids (TSS) | mg/L | 160 | 10.5 | 7.5 | 0.0 | 51.0 |
| Total Nitrogen (TN), unfiltered | mg/L | 297 | 2.0 | 1.1 | 0.7 | 13.0 |
| Total Nitrogen, filtered | mg/L | 52 | 1.2 | 0.3 | 0.8 | 2.2 |
| Total Phosphorus (TP), unfiltered | mg/L | 381 | 0.24 | 0.19 | 0.00 | 1.20 |
| Total Phosphorus, filtered | mg/L | 118 | 0.06 | 0.07 | 0.01 | 0.49 |
| Fecal Coliform (FC) | cfu/L | 266 | 619 | 1917 | 0 | 17000 |

Table A12. Summary statistics for USGS gauge data used in dissolved oxygen regression. Unfiltered samples include the amount of chemical associated with both the particulate and the aqueous fraction, whereas filtered samples include the amount of chemical associated with just the aqueous fraction (Sprague et al., 2017). We use unfiltered observations for TN and TP in our analysis.

| **Variable** | **Model 1** | **Model 2** | **Model 3** | **Model 4** | **Model 5** | **Model 6** |
|---|---|---|---|---|---|---|
| Temp | -0.390*** | -0.369*** | -0.329*** | -0.329*** | -0.325*** |  |
|  | *-0.024* | *-0.017* | *-0.014* | *-0.013* | *-0.013* |  |
| Discharge | 0.002* | 0.001*** | 0.000* |  |  |  |
|  | *-0.001* | *0.000* | *0.000* |  |  |  |
| pH | -0.151 |  |  |  |  |  |
|  | *-0.411* |  |  |  |  |  |
| TSS | 0.021 |  |  |  |  |  |
|  | *-0.023* |  |  |  |  |  |
| TN | -0.829*** | -0.384*** | -0.578*** | -0.566*** | -1.171*** | -2.126*** |
|  | *-0.236* | *-0.124* | *-0.118* | *-0.114* | *-0.245* | *-0.429* |
| TP | -0.38 | -2.371*** | -2.754*** | -3.371*** | -6.481*** | -12.356*** |
|  | *-1.169* | *-0.839* | *-0.755* | *-0.693* | *-1.308* | *-2.285* |
| FC | 0.000** | 0.000** |  |  |  |  |
|  | *0.000* | *0.000* |  |  |  |  |
| TN*TP |  |  |  |  | 1.421*** | 2.723*** |
|  |  |  |  |  | *-0.509* | *-0.9* |
| Constant | 15.671*** | 14.019*** | 14.844*** | 15.159*** | 16.214*** | 14.740*** |

| | | | | | | |
|---|---|---|---|---|---|---|
| | *-2.833* | *-0.412* | *-0.298* | *-0.244* | *-0.448* | *-0.789* |
| Observations | 78 | 204 | 288 | 297 | 297 | 297 |
| Number of sites | 2 | 2 | 3 | 3 | 3 | 3 |
| Adjusted $R^2$ | 0.89 | 0.81 | 0.77 | 0.77 | 0.77 | 0.29 |
| AIC/N | 3.45 | 3.89 | 3.92 | 3.92 | 3.90 | 5.05 |

Table A13. Regression analysis of dissolved oxygen. Standard error in italics, site fixed effects. *** $p<0.01$, ** $p<0.05$, * $p<0.1$. Model three corresponds to the model estimated by (Prasad et al., 2011).

### *Chlorophyll a modeling*

Chlorophyll *a* is the main photosynthetic pigment in phytoplankton and is readily measurable, making it a useful proxy for phytoplankton biomass and possibly for primary production in estuaries. There are many factors at play in predicting chlorophyll concentrations, including climatic and food web pressures, as well as the availability of nutrients, minerals, and other enabling conditions for growth (Ryther & Dunstan, 1971; Hoyer et al., 2002; Bbalali, 2013; Rai & Rajashekhar, 2014). In Narragansett Bay, changes in chlorophyll have been linked to two important stressors: nutrient enrichment and precipitation (NBEP, 2017). Chlorophyll *a* sampling is not conducted at the same USGS gauges we used in the dissolved oxygen modeling and the available data we could retrieve had narrower geographic coverage in the bay. Of these data sources, we used the Narragansett Bay Commission’s monitoring program in the Providence River. This data extends from 2005 – present and includes many of the key predictors indicated as important in the literature (Table A14).

| **Variable** | **Units** | **Obs** | **Mean** | **Std. Dev.** | **Min** | **Max** |
|---|---|---|---|---|---|---|
| Depth | m | 1197 | 0.6 | 1.0 | 0.0 | 24.2 |
| Salinity | ppt | 1130 | 20.6 | 7.6 | 0.2 | 37.1 |
| Temp | deg C | 820 | 16.1 | 7.2 | 0.5 | 32.7 |
| pH | - | 784 | 7.8 | 0.6 | 3.2 | 18.5 |
| Nitrate + Nitrite | mg/L | 910 | 0.25 | 0.31 | 0.00 | 5.02 |
| Nitrite | mg/L | 910 | 0.008 | 0.009 | 0.001 | 0.116 |
| Ammonia | mg/L | 908 | 0.084 | 0.091 | 0.004 | 1.010 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Total Phosphorus (TP) | mg/L | 910 | 0.12 | 0.10 | 0.00 | 0.83 |
| Silicate | mg/L | 898 | 1.07 | 0.61 | 0.02 | 4.73 |
| Total Nitrogen (TN) | mg/L | 609 | 0.78 | 0.32 | 0.28 | 3.09 |
| Total Dissolved Nitrogen | mg/L | 909 | 0.56 | 0.39 | 0.10 | 4.32 |
| ChA | ug/L | 1397 | 13.2 | 20.2 | 0.0 | 262.1 |

Table A14. Summary statistics for chlorophyll *a* sampling from the Narragansett Bay Commission

The data includes PO4 (orthophosphate) versus total phosphorous. To convert between PO4 and TP, we use an approach from (Krumholz, 2012), that relies on estimates from (Nixon et al., 2008) that compares the long run average from 1975 to 2004 of observed inorganic PO4 and TP ratios in large tributary rivers in Narragansett Bay: the Pawtuxet, Woonasquatucket, Blackstone, Moshassuck, and Ten Mile rivers (see table 5.9 in (Nixon et al., 2008)). All of these rivers drain into the Providence River, so these datasets have close spatial overlap. The observed aggregate ratio of PO4 to TP in these rivers is 1 to 1.72, which we used to convert the NBC measurements to TP.

| **Variable** | **LogChA (Model 1)** | **LogChA (Model 2)** | **ChA (Model 3)** | **ChA (Model 4)** |
|---|---|---|---|---|
| Depth | 0.32** | | 5.57** | |
| | *-0.14* | | *-2.77* | |
| Salinity | -0.01 | | 0 | |
| | *-0.01* | | *-0.14* | |
| Temp | 0.09*** | | 1.15*** | |
| | *-0.01* | | *-0.11* | |
| pH | 0.63*** | | 9.60*** | |
| | *-0.13* | | *-2.31* | |
| TN | 0.19 | -0.05 | -9.02 | -13.24* |
| | *-0.21* | *-0.22* | *-6.85* | *-7.82* |
| TP | -1.95** | -3.84*** | -207.28*** | -184.31*** |
| | *-0.9* | *-0.86* | *-50.34* | *-61.67* |
| TN*TP | 1.72*** | 3.81*** | 202.82*** | 194.65*** |
| | *-0.63* | *-0.66* | *-54.06* | *-68.57* |
| Constant | -4.01*** | 2.56*** | -71.90*** | 24.55*** |
| | *-1.07* | *-0.18* | *-17.3* | *-6.26* |
| Observations | 544 | 609 | 544 | 609 |
| AIC/N | 10.56 | 15.29 | 8.02 | 8.364 |

Table A15. Regression analysis of chlorophyll *a*. Standard error in italics. *** p<0.01, ** p<0.05, * p<0.1

The chlorophyll measurements here are count data and are highly skewed in our sample; however the distribution of the residuals after a linear OLS regression appear to be normal, calling into question the value of log-transforming the dependent variable as has been done in other empirical research on chlorophyll *a* concentrations (Hoyer et al., 2002). We investigate a log and non-log dependent variable in the regression analysis (Table A15). Models 1 and 2 are estimated with a log-linear generalized linear model with a poisson distribution and a log link function and robust standard errors. Models 3 and 4 are estimated with ordinary least squares with robust standard errors. We do not include fixed effects as all locations are very close to each other in the Providence River and monitored under the same sampling protocol.

As with the dissolved oxygen regression model, we observe that nitrogen and phosphorus play are strongly correlated with chlorophyll *a*, as are temperature, water depth, and pH. Similar data limitations also play a role in selecting model 4 for our predictive model, as well as residual normality and the practical challenges of predicting arithmetic mean values in the original scale when using a log transformation. The predictive model is: $ChA = 24.55 - 13.24Tn - 184.31TP + 194TN * TP$. All of the omitted variables are positively correlated with chlorophyll *a* counts, so we expect that function tends to underestimate counts.

*Enterococcus modeling*

Unlike the models for chlorophyll *a* and dissolved oxygen, the literature on fecal coliform (FC) and enterococcus, two closely linked indicators for pathogenic bacteria contamination in water, tends to focus less on linking to simultaneously sampled in situ water quality characteristics and more towards landscape level point and non-point source interventions directly. (Fisher et al., 2000) suggests that forest cover could increase FC concentrations from wild animals; however, the study is not robust statistically and is more qualitative in nature. (Frenzel & Couvillion, 2002) look at the effect of population density and sewer/septic systems on FC concentrations, finding that higher population density was associated with higher FC concentrations and sewered areas were associated with higher FC concentration than those served by septic systems, suggesting that the difference is driven by the fact that sewered areas had storm drains that discharge directly into streams and septic areas do not. (Sowah et al., 2014; Sowah et al., 2017) find a similar result in a multivariate regression with pooled data from spring, summer, and fall, while finding little evidence of a correlation with land use when including factors like impervious cover, agricultural land, and forested land. With pooled data across the year, the only statistically significant finding was that impervious cover tends to reduce markers of pathogenic bacteria.

Several other studies have hypothesize that land cover maps could have predictive power for estimating bacteria concentrations in adjacent waterbodies. (Tong & Chen, 2002) found positive and significant relationships of fecal coliform to commercial, residential, and agricultural land and a significant and negative relationship to forested land. (Walters et al., 2011) took a similar approach to (Tong & Chen, 2002) in an analysis in California estuaries using the HUC 12 level watershed as the analysis unit, with a multivariate regression analysis showing a significant positive relationship between bacteria and urban land cover. Salinity and rainfall were also largely significant across a variety of model specifications. Model fit was generally poor though, with an $R^2$ was between .11 and .23. Finally, (Vitro et al., 2017) features lots of mixed results with generally poor fit for land cover types besides urban land cover, similar to (Walters et al., 2011) and (Sowah et al., 2017), with urban land cover associated with greater bacterial contamination.

| **Variable** | **Units** | **Obs** | **Mean** | **Std. Dev.** | **Min** | **Max** |
|---|---|---|---|---|---|---|
| Enterococcus | cfu/100 mL, geo mean | 380 | 105 | 553 | 5 | 6867 |
| Enterococcus | cfu/100mL, arith mean | 380 | 214 | 1142 | 7 | 14825 |
| Temperature | deg F | 380 | 68 | 7 | 42 | 85 |
| Prior 7 day precip | inches | 380 | 0.97 | 1.01 | 0 | 3.76 |
| HUC12 Size | $km^2$ | 380 | 51 | 20 | 24 | 91 |
| HUC12 Urban | % | 380 | 0.61 | 0.21 | 0.25 | 0.85 |
| HUC12 Forest | % | 380 | 0.22 | 0.11 | 0.08 | 0.40 |
| HUC12 Ag | % | 380 | 0.05 | 0.08 | 0.00 | 0.24 |
| HUC12 WWTF | % | 380 | 0.57 | 0.30 | 0.04 | 0.97 |
| HUC12 OWTS | per $km^2$ | 380 | 42 | 28 | 0 | 113 |

Table A16. Summary statistics for aggregated data based on RI Department of Health bacteria sampling

| Year | Station | Zone | Count | Mean seven-day precip (May - Sept) | Std Dev | Min | Max |
|---|---|---|---|---|---|---|---|
| 2001 | PVD | 1 | 153 | 0.97 | 1.14 | 0 | 4.76 |
| 2001 | UUU | 2 | 153 | 0.76 | 0.78 | 0 | 3.58 |
| 2011 | PVD | 1 | 153 | 1.12 | 1.08 | 0 | 3.89 |
| 2011 | UUU | 2 | 153 | 0.79 | 0.85 | 0 | 3.35 |
| 2006 - 2015 | PVD | 1 | 1676 | 0.86 | 1.02 | 0 | 7.03 |
| 2006 - 2015 | UUU | 2 | 1676 | 0.72 | 0.90 | 0 | 6.25 |

Table A17. Rainfall by zone at TF Green (PVD) and Newport (UUU) airports from Iowa State Environmental Mesonet. 2006 – 2015 data were used to estimate the model, and 2001 and 2011 values were used for prediction.

| | Total | | Ratio to Total Area | |
|---|---|---|---|---|
| Variable | Zone 1 | Zone 2 | Zone 1 | Zone 2 |
| WWTF (km2) | 254.29 | 73.56 | 0.33 | 0.2 |
| OWTS (#, #/km2) | 39121 | 29290 | 50 | 80 |

Table A18. Wastewater treatment systems within the network for the period 2001 - 2011

We collected data from the Rhode Island Department of Health that included summer (May – Sept) sampling for enterococcus over the years 2006 – 2016 in Narragansett Bay (Table A16). We supplemented this data with data on prior 7 day rainfall for the period 2006 – 2016 from the Iowa State University's environmental mesonet. From this source, we gathered daily precipitation data for the airports TFGreen (PVD) and Newport (UUU), which are in zone 1 and zone 2 respectively, and created a variable indicating a moving sum of 7 day antecedent rainfall approach based on (Walters et al., 2011). This data was attached to the geolocated enterococcus data based on whether it was closer to PVD or UUU (Table A17.). Similarly, we added data on land cover to each observation based on the closest HUC 12 subwatershed land cover proportions in the classes urban, forested, and agricultural (Table A16). These are the crosswalked aggregated land cover classes (classes from the 2011 National Land Cover Database):

- Urban (developed open space, developed low intensity, developed medium intensity, developed high intensity)
- Agriculture (pasture, cultivated crops)
- Forest (deciduous, evergreen, mixed, grassland)

Finally, we added data related to the wastewater network coverage (coverage area within nearest HUC 12 divided by HUC 12 overall area) and the density of septic systems in the nearest HUC 12 (#/km$^2$). These layers were sourced from the Narragansett Bay Estuary Program (Table A18).

Data on enterococcus is generally not randomly sampled as noted by (Vitro et al., 2017) as sampling tends to be done for specific reasons, like beach recreation or measuring progress in areas with poor water quality. As a result, our regression specifications were again partially limited in what we can use by the need for out of sample prediction throughout Narragansett Bay. We include land cover (urban, forest, agriculture), percentage of adjacent HUC 12 subwatershed served by a wastewater treatment network, watershed size (km$^2$), septic density, prior 7 day rainfall, and temperature in the regression models, but are forced to remove temperature in our final predictive model due to a lack of a representative mean value for each zone in the bay.

We employ a log transform of the dependent variable following guidance in the literature in a generalized linear regression model, where the dependent variable is alternatively considered as a geometric or arithmetic mean depending on the model specification. Geometric means are used to avoid zero-inflation in bacteria sampling data analysis (Vitro et al., 2017). Like with the chlorophyll *a* modeling, we estimate all models here using a generalized linear model with a Poisson error structure and log link function with robust standard errors.

| **Variable** | **Geo Mean 1** | **Geo Mean 2** | **Geo Mean 3** | **Ari Mean 1** | **Ari Mean 2** |
|---|---|---|---|---|---|
| Temperature | -0.03 | -0.03 | | -0.01 | |
| | *-0.03* | *-0.02* | | *-0.03* | |
| Prior 7 day precip | 0.55*** | 0.55*** | 0.55*** | 0.65*** | 0.65*** |
| | *-0.17* | *-0.17* | *-0.17* | *-0.18* | *-0.18* |
| HUC12 Size | 0.01 | | | 0.03 | |
| | *-0.02* | | | *-0.02* | |
| HUC12 Urban | 20.29 | 20.47* | 20.88* | 13.21 | 14.35 |
| | *-12.97* | *-11.92* | *-12.19* | *-15.76* | *-11.68* |
| HUC12 Forest | -0.32 | -0.39 | -0.21 | -5.59 | -4.91 |
| | *-8.29* | *-8.16* | *-8.16* | *-9.19* | *-7.63* |
| HUC12 Ag | -1.26 | 2.25 | 2.19 | -14.03 | -5.58 |
| | *-13.59* | *-9.26* | *-9.28* | *-15.11* | *-9.91* |
| HUC12 WWTF | -18.83** | -18.78** | -19.32** | -18.90* | -18.86** |
| | *-8.64* | *-8.16* | *-8.29* | *-10.65* | *-8.4* |
| HUC12 OWTS | -0.08** | -0.08** | -0.09** | -0.10* | -0.10*** |
| | *-0.04* | *-0.04* | *-0.04* | *-0.05* | *-0.04* |
| Constant | 6.93 | 7.05 | 5.41 | 11.74** | 11.65** |
| | *-5.28* | *-5.36* | *-4.96* | *-5.73* | *-4.83* |
| Observations | 380 | 380 | 380 | 380 | 380 |
| AIC | 143336 | 143868 | 145084 | 298566 | 304342 |

Table A19. Regression analysis of enterococcus. Standard error in italics. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

We find across models qualitatively similar results to several recent studies, including a weakly positive association between urban land cover and enterococcus concentrations and no significant effects for other land use, as well as a strongly positive correlation with recent rain events (Table A19). More wastewater treatment network coverage and more densely distributed septic systems are associated with a decrease in bacterial concentrations. This is an interesting result in that wastewater treatment networks' ability to reduce bacterial contamination of adjacent waterbodies is often done by eliminating combined sewer overflow systems and increasing treatment capacity during acute precipitation events, and not necessarily by expanding coverage. We select model 3 for our final predictive model which varies by zone based on the landscape characteristics included in the regressions. We do not vary any of the predictors in this model across scenarios aside from land use and rainfall, for which we use values from 2001 and 2011 from the NLCD and Iowa State Environmental Mesonet respectively.

Zone 1: $E = e^{(-5.47+0.55Rain+20.88Urban-0.21Forest+2.19*Ag)}$

Zone 2: $E = e^{(-5.65+0.55Rain+20.88Urban-0.21Forest+2.19*Ag)}$

*Dam modeling*

The amount of sediment or nutrient retained by a dam is modeled implicitly as a function of the measured export rate (inverse of the retention) of the dam multiplied by the sediment or nutrient load flowing through that dam. For one dam this is simply:

$$E_i = \sum_{j \in upstream\ from\ i} (L_j \cdot (1 - R_i))$$

Where $E_i$ is the effective export from dam *i*, $L_j$ is the load reaching dam *i* from an upstream pixel from dam *i,* and $R_i$ is the retention rate of dam *i* (proportion of pollutant retained). This calculation becomes complex in the case of a load passing through several upstream dams before reaching *i,* and can be calculated as follows

$$E_i = \sum_{j \in upstream\ from\ i} \left( L_j \cdot \prod_{\substack{k \in upstream\ and\ including\ i \\ but\ downstream\ from\ j}} (1 - R_k) \right)$$

For the analysis of nitrogen retention, we use the dataset of dams from (Gold et al., 2016), which contains the locations of dams as lat/long points (n = 352) as well as the percent of TN load retained annually derived for all known dams in the watershed. For sediments, we use the locations of dams based on the US Army Corps of Engineers National Inventory of Dams dataset, since the Gold et al. (2016) data do not include information on reservoir storage capacity, which was necessary for estimating their retention. This resulted in 404 dams considered for modeling sediment retention. We estimated the percent of sediment load retained annually based on (Brune, 1953), which calculates the trap efficiency of reservoirs based on their storage capacity and watershed area.

We use the same datasets to estimate dam retention in the retrospective analysis for both 2001 and 2011 since data on impoundment dates were incomplete. Dam construction and removal within the time period 2001 to 2011 was negligible; most of the dams in this area were constructed decades or even centuries ago (Gold et al., 2016) and removals are rare.

We derived the upstream contributing area for each dam (vector polygon dataset) using the InVEST RouteDEM tool (Sharp et al., 2016) and the USGS 1/3 arc second NED DEM. Assuming the resulting watersheds are hydrologically sound, then dam *i* can be considered downstream of dam *j* if dam *j*'s watershed is contained by *i*'s. This is not necessarily the case – even the National Hydrography Database maintained by the United States Geological Survey has significant issues with this (Leonard et al., 2017). We manually inspected the resulting watersheds from RouteDEM for consistency and used this relationship to calculate an effective per-pixel export rate for the area of analysis, and in turn multiplied it by the base pollutant load map to determine final effective total export.

One caveat to note is that some dams reported a *negative* nitrogen retention rate indicating more nitrogen was exported from a dam than flowed into it, based on the functional form of the empirical prediction regression in (Gold et al., 2016). This is problematic for the analysis presented here since it is possible through nested multiplication to achieve an export rate that violates conservation of mass. We believe that the negative retention rates are an artifact of the linear functional form used by Gold et al. (2016) in their empirical assessment of retention rates and should have been estimated using an alternate functional form. They state "the empirical database we used to relate lake and reservoir properties to N removal did not include any sites with <10% removal." We do not have access to their full dataset to rerun their analysis using a more appropriate functional form. Thus, we treated negative retention rates as 0, or a 100% export rate for that dam. This affected 130 of 352 dams.

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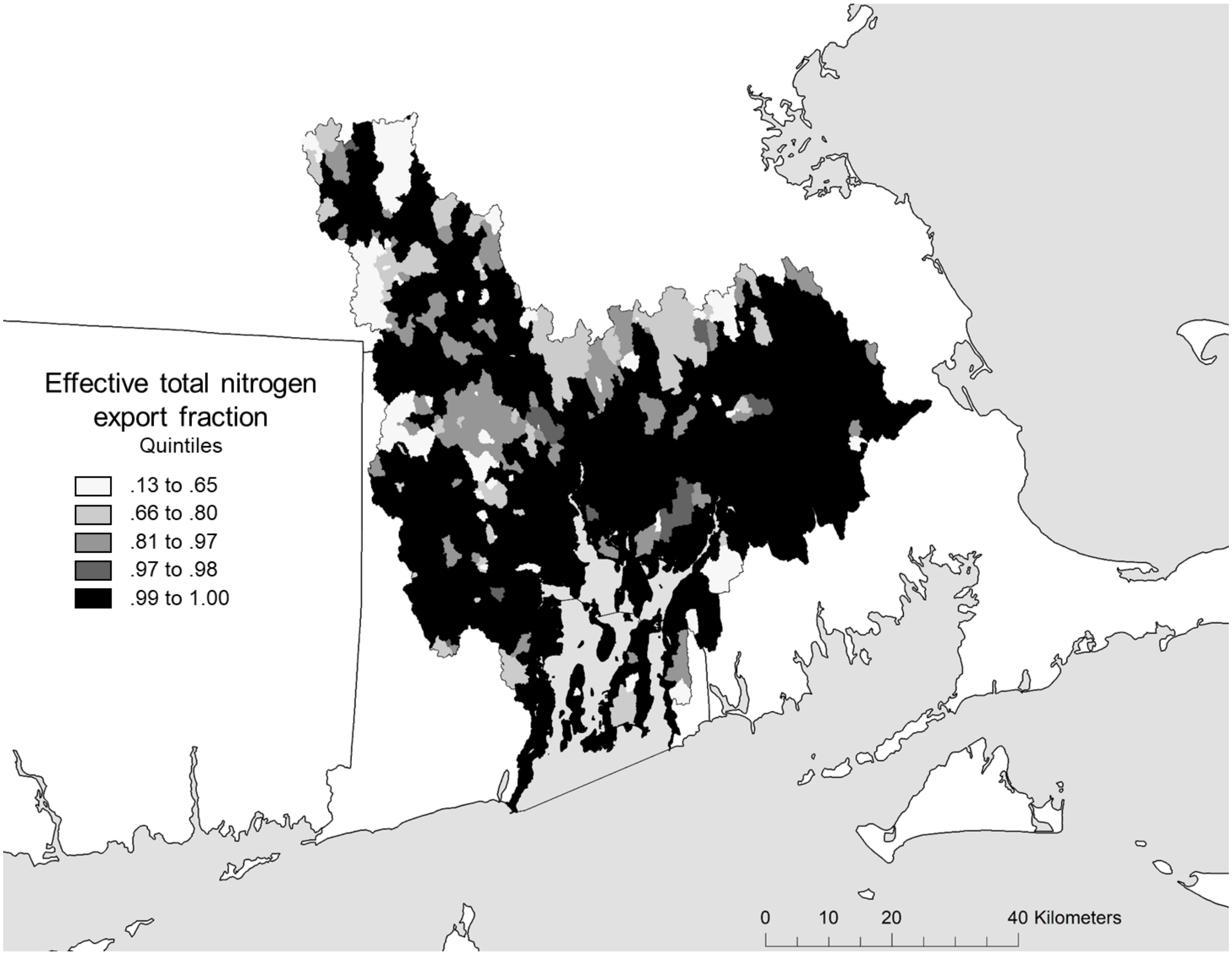

Figure A2. Effective non-point source total nitrogen export ratio to Narragansett Bay based on cumulative retention effect of dams in the watershed

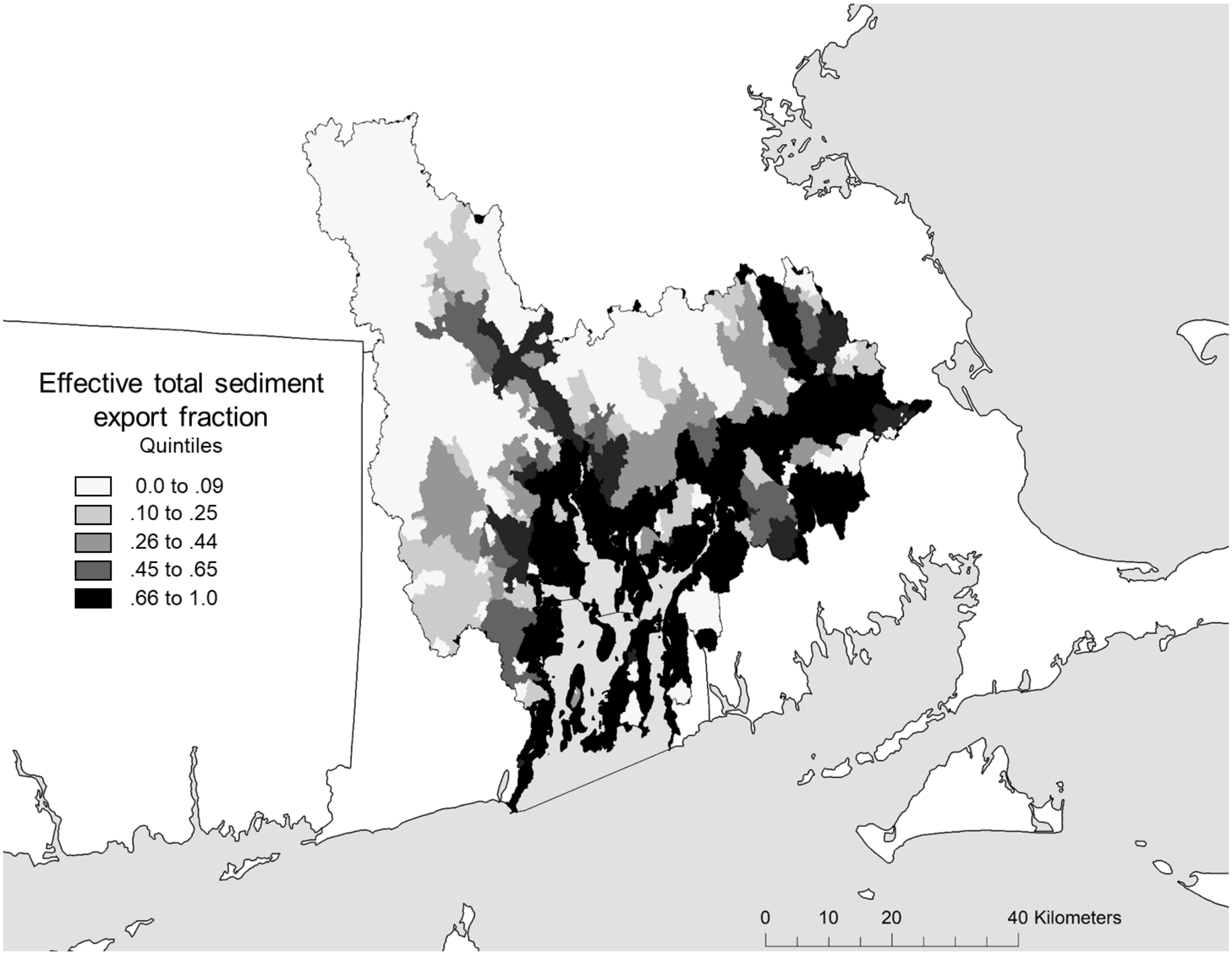

Figure A3. Effective non-point source sediment export ratio to Narragansett Bay based on cumulative retention effect of dams in the watershed

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