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A rapid watershed assessment approach for assessing the condition of small, coastal watersheds: Protocol and case study

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ABSTRACT

Human population pressures in coastal drainage basins have increasingly contributed to degraded estuarine habitats. Yet, there are no approaches for rapidly characterizing watersheds and for identifying sources of environmental degradation that affect estuarine habitat and water quality. A rapid watershed assessment (RWA) protocol is described that uses 15 indicators from both contributing watersheds and receptor estuaries to assess coastal watershed condition. The protocol was applied to five small, coastal watersheds to illustrate strengths and limitations of the approach and its sensitivity in quantifying differences in condition among the watersheds.

The RWA found that the poor condition of the tested coastal watersheds were due to both problems in the contributing watersheds (primarily due to agriculture and field drainage ditches) and problems in the receptor estuaries (primarily due to pollution leading to closed shellfish beds and channel maintenance detrimentally affecting benthic habitats). Indicator data were robust enough to differentiate variations in condition among indicators and sufficient to identify problems that needed to be addressed in contributing watersheds and receptor estuaries. Thus, indicator output can be used to diagnose problems in ways that can guide planning at a small watershed scale, identify ways to minimize future impacts, and help prioritize strategies for improving or enhancing current conditions. Because the RWA protocol integrates the types of data that are readily available for small estuaries, it provides a useful framework that could be adapted for use in small coastal watersheds and sub-estuaries elsewhere.

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1. Introduction

Assessment methods have advanced rapidly over the past two decades. Most assessments methods have been tailored to the needs of individual program objectives (Stein et al., 2009). Some methods focus on water quality (Karr, 1991), others on wetlands (Brooks et al., 2009; Smith et al., 1995), some on estuaries (Diaz

et al., 2004), and yet others on terrestrial ecosystems (Andreasen et al., 2001).

Within this broad range, assessments have been developed for a variety of administrative and policy frameworks ranging from global ecosystem services (MEA, 2005), national status and trends for wetlands (USFWS status), and assessments for prioritizing wetland restoration opportunities in watershed planning (Rheinhardt et al., 2007a). In the U.S., most assessments are focused on addressing water quality impairment and mitigation/restoration that originate with Clean Water Act legislation. The complexity of approaches ranges from models that determine loading rates (Total Maximum Daily Load: TMDL) to field surveys of streams using indicators of biological integrity (Index of Biotic Integrity: IBI) to protocols for determining wetland condition

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relative to functional capacity (Hydrogeomorphic approach: HGM).

Even with all this progress in developing rapid assessment protocols, there are no available protocols designed to assess the condition of small coastal drainage basins and provide the type of information needed to identify where efforts should be focused to improve condition. At least 27% of the world’s population currently (circa 1990) lives within 100 km of the coast (Small and Nicholls, 2003) and growth has and is expanding rapidly. As a consequence, resource extraction and landuse changes are detrimentally affecting the condition of coastal estuarine watersheds, which has led to increased coastal eutrophication and the collapse of fisheries. A watershed-scale, scientifically-based approach is needed that can be adapted to help coastal resource managers identify stressors and solutions at regional scales.

The intent here is to (1) outline the development of a rapid watershed assessment (RWA) approach and (2) test the approach using data from five watersheds of a North Carolina estuary (Fig. 1). The RWA takes a holistic approach in characterizing watershed condition by recognizing that estuaries are the receptors of the downstream effects of activities within contributing watersheds, and so it explicitly links these activities with the

ecological condition of watersheds. Although the RWA protocol was designed to use the types of data available for coastal watersheds in North Carolina (ECU and ED, 2006), similar indicators, based on locally available data, could be used in small coastal watersheds elsewhere.

2. Methods

2.1. Stakeholder involvement

The protocol was designed for use by the North Carolina Ecosystem Enhancement Program (NCEEP) and the North Carolina Division of Marine Fisheries (NCDMF) to provide a scientifically defensible method for identifying and prioritizing watersheds where restoration would be most beneficial for estuarine habitats. Development of the RWA protocol was a consensus-building effort among a broad range of interest groups ranging from scientists to regulatory agencies to environmental non-governmental organizations (NGOs) (ECU and ED, 2006). The effort included input from at least 30 scientists and stakeholders involved in various aspects of estuarine research, policy making, and regulatory enforcement in North Carolina. The entire process took two years and about three meetings

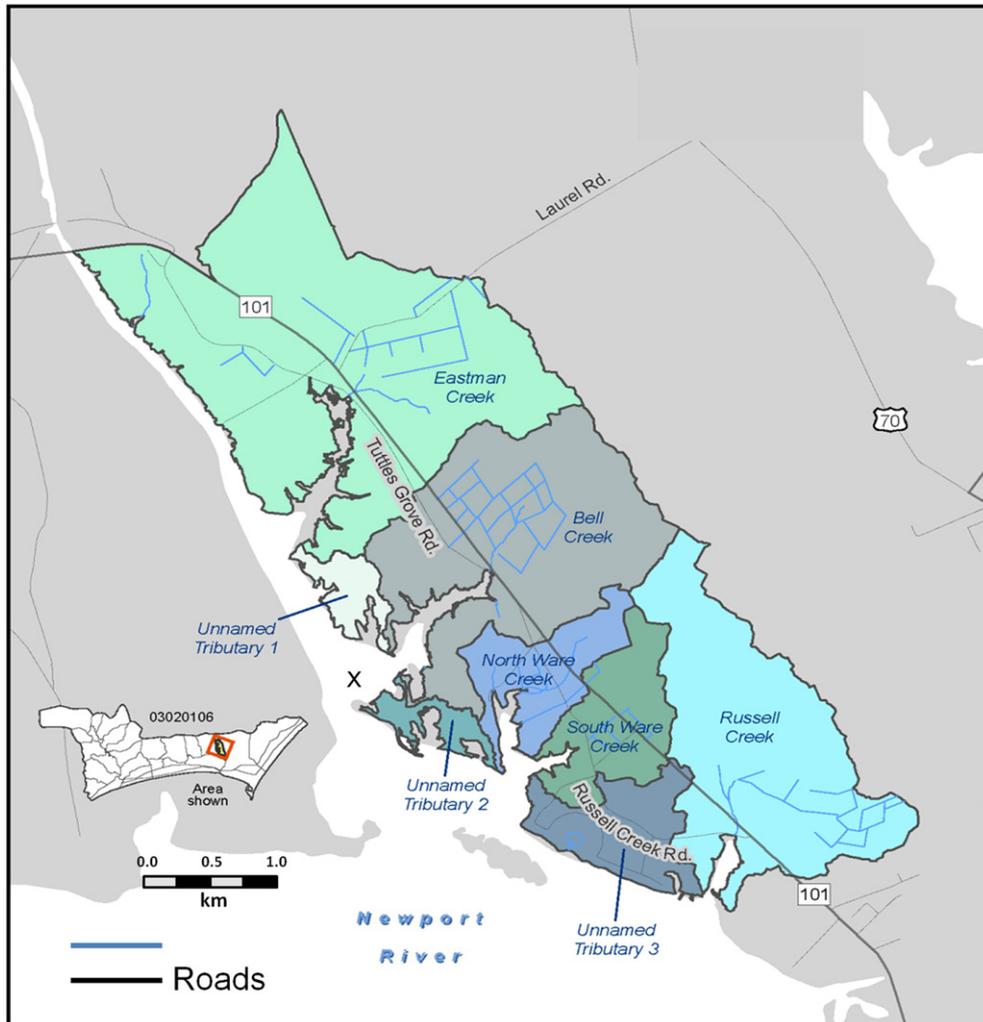


Fig. 1. Location of watershed case study in a coastal plain lagoonal estuary (X = N34.7861, W-76.6845), located 8 km north of Beaufort, NC, USA.

among all stakeholders, but numerous other meetings were held by a subcommittee called the Habitat and Implementation Committee. The stakeholders were kept informed of the subcommittee's progress through emails, phone calls, and a web site established to distribute information. The subcommittee also requested input from other stakeholders throughout the process. However, the intent of involving stakeholders went beyond consensus building to gain broad acceptance of the approach; stakeholder meetings were a conduit for focusing diverse interests and perspectives on the complex interplay among stressors originating both in contributing watersheds and within receiving estuaries. This insured that all sources and relative magnitude of stressors in coastal habitats were identified, that regulatory agencies would ultimately adopt the protocol, and that resource managers would likely use it.

2.2. Watershed bounding

A watershed size was chosen that would be sufficient for influencing an identifiable portion of the downstream estuary. The entire landscape does not necessarily contribute to a receiving estuary, nor does its contribution to condition have to be precisely quantified. However, there are causal connections between alterations to a contributing drainage basin and the condition of the basin's receiving estuary that can be reasonably used to delineate watersheds based on connections between activities and conditions in the watershed and receiving estuarine waters. Best professional judgment and best available science were applied in deciding on the appropriate watershed size for assessment, but since the RWA approach was designed for small, coastal watersheds, all watersheds were relatively small: 94–650 ha in size.

2.3. Description of indicators and scoring methods

A wide variety of data are routinely collected in estuaries to provide managers and policymakers with information they use to understand, monitor, and communicate changes in estuarine condition. Although the quantity, quality, and type of data vary considerably worldwide, data collection efforts usually reflect the local needs and available resources of managers and policymakers. It is these data that can provide the basis for creating environmental indicators, which can be used to efficiently provide insight into a resource's condition. A thorough review of the history and development of indicators is beyond the scope of this paper, but the approach described in this paper was to characterize the degree of estuarine degradation by expressing condition relative to the unaltered condition (i.e., condition without human alteration).

Stakeholders identified three major characteristics of coastal watershed condition (hydrologic regime, material flux and pollution, and aquatic habitat) and the stressors related to them. They then identified what data (esp. geospatial data) were readily available and being routinely collected by state and federal agencies in estuaries and their contributing watersheds in North Carolina. Based on these data, 15 indicators were identified that could be used to assess watershed condition relative to the three condition categories.

Some indicators are specific to conditions that occur in the contributing watershed, others to conditions in the receiving estuary. This differentiation was intentional in order to enable users to identify the sources of stressors. The European Environment Agency defines these types of indicators as "performance indicators" because they "measure the 'distance(s)' between the current

environmental situation and the desired situation (target)" (Smeets and Weterings, 1999).

It was also intended that indicators used to characterize condition could evolve as additional data sources become available and allow new indicators to be consolidated with the other indicators based on specific needs and available information. Although there is some redundancy in information used to score indicators, which leads to autocorrelation among scores, the chosen indicators were intended to identify where restoration or enhancement could improve or protect estuarine condition. The consensus among stakeholders was that the approach would be more transparent if users examined and reported each indicator score independently rather than consolidate scores to provide a single watershed condition score. However, given that independent scores are obtained in the process, end users could design a mechanism for combining scores to classify watersheds by type of alteration or prioritize watersheds for restoration.

Relative condition was initially determined by a numeric score, which was then converted to a condition category ranging from least to most altered: **Relatively Unaltered, Somewhat Altered, Altered, and Severely Altered**. Figures A.1–A.3 in the appendix provide a narrative description of these condition categories for each indicator. The intent of initially assigning a numeric score for indicators was to provide a quantitative approach that would provide repeatable values among users (Whigham et al., 1999) and insure a consistent relationship between measurements and scores. With this approach, condition could be defined as a relative degree of deflection from the **Relatively Unaltered** condition, which recognizes that all ecosystems have been altered to some degree and are not pristine. Equivalent terms are historical condition (Hobbs et al., 2009) and reference condition (Karr, 1991).

Numeric values range between 0 (most altered) and 100 (least altered) and the range of numeric values within a condition category is the same for all indicators (e.g., **Altered** always ranges between 30 and 59). In most cases, one or more of the condition threshold boundaries were based on scientific data or on state water quality standards, when applicable. A table for converting a raw indicator measurement (metric) to a condition score is provided in Table 1. To facilitate interpretation, the 15 indicators are aggregated into three, broad, watershed function categories: hydrologic regime, materials flux/pollution, and aquatic habitat. The data layers used for scoring these indicators are summarized in Table 2.

2.3.1. Hydrologic regime indicators

Five indicators associated with landuse characteristics of contributing watersheds were chosen to assess the extent to which the hydrological regime has been altered relative to an unaltered reference condition (Table 2). Indicators of hydrologic regime focus on the timing and magnitude of water flowing to receiving estuaries and characterize the degree to which the residence time of water in the contributing basins has been altered.

2.3.1.1. Indicator 1: Riparian-stream condition (1a: riparian zone; 1b: channel). This indicator is a composite evaluation of the ecological condition of both the riparian zone (1a) and adjacent channel (1b) of tributary streams, using the riparian assessment approach of Rheinhardt et al. (2007b). Riparian condition is affected by riparian forest composition, age, and structure of vegetation and alterations to the floodplain and buffer zones. Stream channel condition is degraded by intensity of channelization or degree of incision,

Table 1
Relationship between indicator metric scores and the four condition categories. A maximum condition score of 100 denotes no alteration.

CONDITION		RELATIVELY UNALTERED			SOMEWHAT ALTERED					ALTERED					SEVERELY ALTERED							
Condition Score		100	95	90	85	80	75	70	65	60	55	50	45	40	35	30	25	20	15	10	5	0
Indicator	Metric																					
1. Riparian-stream condition	Riparian Assessment Procedure score	100.0	95.0	90.0	85.0	80.0	75.0	70.0	65.0	60.0	55.0	50.0	45.0	40.0	35.0	30.0	25.0	20.0	15.0	10.0	5.0	0.0
2. Extent of ditching	% drainage from ditches (relative to natural channels)	See Indicator description (Fig. 1)			1.4	3.1	4.8	6.6	8.3	10.0	14.5	15.0	17.5	20.0	22.5	25.0	29.2	33.3	37.5	41.7	45.8	50.0
3. Wetland conversion	% wetland converted	0.0	2.5	5.0	8.6	11.9	15.2	18.4	21.7	25.0	29.3	33.4	37.6	41.7	45.9	50.0	58.3	66.7	75.0	83.3	91.7	100.0
4. Land-use effects on runoff	% increase in run-off from land-uses	0.0	4.5	9.1	11.2	12.8	14.3	15.9	17.4	19.0	21.9	24.3	26.8	29.2	31.6	34.0	40.5	47.4	54.3	61.2	68.1	75.0
5. Watershed impervious area	% impervious area	0.0	3.6	7.3	8.6	9.2	9.9	10.6	11.3	12.0	14.5	16.4	18.3	20.2	22.1	24.0	28.3	32.7	37.0	41.3	45.7	50.0
6. Land-use effects on nutrient loading	% increase in nutrient loading from land-uses	0.0	22.7	45.5	60.2	73.0	85.7	98.5	111.2	124.0	135.2	148.0	160.7	173.5	186.2	199.0	210.3	223.3	236.2	249.1	262.1	275.0
7. Point sources of pollution	% increase in nutrient loading from NPDES	0.0	22.7	45.5	60.2	73.0	85.7	98.5	111.2	124.0	135.2	148.0	160.7	173.5	186.2	199.0	210.3	223.3	236.2	249.1	262.1	275.0
8. Concentrated sources of pollution	% increase in nutrient loading from CAFOs	0.0	22.7	45.5	60.2	73.0	85.7	98.5	111.2	124.0	135.2	148.0	160.7	173.5	186.2	199.0	210.3	223.3	236.2	249.1	262.1	275.0
9. Near-shore pollution ^a	% nearshore (0.4 km) impervious area OR number of boat slips per km of shoreline	0.0	0.9	1.8	3.1	4.5	5.9	7.2	8.6	10.0	12.8	15.0	17.3	19.5	21.8	24.0	28.4	32.8	37.1	41.4	45.7	50.0
10. Shellfish closures	% Shellfish waters Conditionally Approved, but Closed and Prohibited areas	0.0	4.5	9.1	12.1	14.7	17.2	19.8	22.4	25.0	29.3	33.4	37.6	41.7	45.9	50.0	54.2	58.3	62.5	66.7	70.8	75.0
11a and b. Water quality - eutrophication and toxicants ^b	% samples that exceed threshold levels	0.0	0.5	0.9	2.1	3.5	4.9	6.2	7.6	9.0	11.2	12.8	14.3	15.9	17.4	19.0	21.4	23.1	24.8	26.6	28.3	30.0
12. Water column transparency	% samples that exceed threshold levels	0.0	0.5	0.9	2.1	3.5	4.9	6.2	7.6	9.0	11.2	12.8	14.3	15.9	17.4	19.0	21.4	23.1	24.8	26.6	28.3	30.0
13. Impediments to anadromous fish migration ^c	% of tributary streams impacted by culverts	0.0	2.3	4.5	5.6	6.2	6.9	7.6	8.3	9.0	11.9	14.3	16.8	19.2	21.6	24.0	25.7	26.6	27.4	28.3	29.1	30.0
14. Impediments to tidal circulation	% of original shoreline bulkheaded or wetlands filled	0.0	2.3	4.5	5.6	6.2	6.9	7.6	8.3	9.0	11.9	14.3	16.8	19.2	21.6	24.0	25.7	26.6	27.4	28.3	29.1	30.0
15. Maintained channels, trawl areas, and SAV scars	% of benthic area altered	0.0	2.3	4.5	6.2	7.8	9.3	10.9	12.4	14.0	16.2	17.8	19.3	20.9	22.4	24.0	26.4	28.1	29.8	31.6	33.3	35.0

^a Calibrated for % nearshore impervious surface. See Indicator descriptions for scoring with respect to number of boat slips/km of shoreline

^b Toxicants include those in water, sediment, and tissue samples.

^c Only applicable where habitat has been available historically.

the quality and quantity of in-stream detritus, and extent of bank erosion (Hardison et al., 2009; Kroes and Hupp, 2010; Yarbrough et al., 1984). Data for this indicator requires data collection along a representative sample of streams in the stream network (Rheinhardt et al., 2007a).

urban land use, has been demonstrated to result in stream channel degradation (Booth, 2000). Therefore, 20–34% urban or agricultural land use was used to define the **Altered** condition category while the **Severely Altered** category was defined as >35% urban/suburban land cover (Table 2). The equation used to measure the indicator is:

$$\text{Land use effects on runoff (\%)} = \left(\frac{\text{area of urban development} + \text{area of agriculture}}{\text{total area of watershed}} \right) \times 100$$

2.3.1.2. Indicator 2: Extent of ditching. This indicator evaluates the proportion of mapped drainage channels relative to mapped natural channels. Drainage ditches intercept polluted groundwater flow and convey stormwater, nutrients, and sediments downstream quickly so that there is less time for in-stream processing of pollutants. The indicator is intended to capture a drainage effect due to a greater and more rapid delivery of water to receiving estuarine waters. Within each watershed, the total length of mapped channels (blue lines) was measured and separated into natural stream channel and drainage ditch (man-made channel). We assumed that a >25% increase in network channel length due to ditches would have significant effects on water delivery in a small watershed, i.e., defining the **Severely Altered** condition (Table 2). Other thresholds for condition categories were arbitrarily chosen. The equation used to measure the indicator is:

$$\text{Extend of ditching (\% ditching)} = \left(\frac{\text{total length of ditches}}{\text{total length of natural channel}} \right) \times 100$$

2.3.1.3. Indicator 3: Wetland conversion. This indicator estimates the extent to which wetlands within a contributing drainage basin and its receiving subestuary have been converted to other (non-wetland) land uses. Any maps that can provide historic wetland extent and current wetland area would be suitable as input data for this variable. A map of hydric soils can provide the historic context. Condition category thresholds were arbitrarily chosen, with wetland conversion of >50% representing the **Severely Altered** condition (Table 2). The equation used to measure the indicator is:

$$\text{Wetland conversion (\%)} = \left(\frac{\text{area of mapped hydric soils} - \text{area of mapped wetlands}}{\text{total area of mapped hydric soils}} \right) \times 100$$

2.3.1.4. Land-use effects on runoff. This indicator evaluates the effect of land-use changes on the quantity and velocity of stormwater runoff within a watershed. We assumed that a naturally vegetated landscape (forest in the study area) was the **Relatively Unaltered** condition. For each watershed, percent cover of non-forest landuse was determined by dividing the area of land occupied by Urban Development and Agriculture by the total area of the watershed. Ten percent imperviousness, which corresponds to 30%

2.3.1.5. Indicator 5: watershed impervious area. This indicator evaluates the effects of impervious surfaces associated within “Developed” land use categories and so includes parking lots, buildings, roads, driveways, and sidewalks (Mallin et al., 2009). Impervious surfaces increase the quantity and velocity of stormwater runoff flowing from a watershed to its receiving estuary. Methods to derive the impervious index are explained in Yang et al. (2003).

The range of values for the four condition categories were derived from those of Zielinski (2002), who identified three categories of streams, defined by the percentage of imperviousness (in parentheses) of their watersheds: sensitive stream (1–10%), impacted stream (11–25%), and altered stream (>25% impervious). Using this categorization as a basis, the values for each condition category for this indicator were modified slightly to reflect stormwater requirements established for commercial shellfish harvesting in coastal waters of North Carolina (i.e., classification SA: 15A NCAC 02H.1005). Following this adjustment, 24% was defined as the threshold for the **Severely Altered** condition while the other categories reflect established state stormwater requirements (Table 2). The equation used to measure the indicator is:

$$\text{Watershed impervious area (\%)} = \left(\frac{\text{area of urban impervious land use}}{\text{total area of watershed}} \right) \times 100$$

2.3.2. Materials flux/pollution indicators

Three indicators, associated with landuse characteristics of contributing watersheds, were chosen to characterize the amount of

nutrients that are potentially being exported to receiving estuaries and originating from point-source, non-point source, and concentrated sources (Table 3). These Materials flux/pollution indicators focus on the increased loading of nutrients in contributing watersheds relative to a forested (unaltered) watershed. Nutrient concentrations are rarely monitored in small coastal streams in North Carolina. Thus, data bases of discharge permits and landuse types are used as an alternative for inferring water quality of streams.

2.3.2.1. *Indicator 6: Land-use effects on nutrient loading.* This indicator evaluates the extent to which non-forest land cover increases nutrient export, particularly nitrogen, from a coastal watershed to its estuary. It was assumed that forested watersheds only export nitrogen received through atmospheric deposition and nitrogen fixation. Therefore, Agriculture and Urban Development land cover types were used to characterize the increase in nutrient loading in a watershed, largely a result of fertilizer application. Increased nutrient export was expressed relative to nitrogen loading coefficients under a forested condition.

Nitrogen export coefficients for coastal plain North Carolina were obtained from four different sources (Beaulac and Reckhow, 1982; Dodd and McMahon, 1992; Dodd et al., 1992; Lunetta et al., 2005) and averaged to estimate export coefficients for the three different land uses (Agriculture = 10.3 kg N/ha/year (9.2 lb N/acre/

System (NPDES) permitted facilities.¹ Where NPDES monthly reports are available, nitrogen loads are calculated by multiplying recorded flows by reported concentrations. These monthly loads are then summed to provide an annual estimate of N export. For cases in which nitrogen export data are not available, we assumed a conservative concentration of 20 mg N/L multiplied by 80% of permitted flow.

To determine the percent increase in nutrient loading due to point sources relative to loading that would occur under a totally forested land use, loading was estimated by adding the point source contribution to the N contribution of a naturally forested watershed (1.8 kg N/ha × watershed area) and dividing the sum by the N contribution of a forested watershed. The same thresholds marking the transitions between condition categories for Indicator 6 (Land-use effects on nutrient loading) were applied to this indicator (Table 2). The equation used to measure the indicator is:

$$\text{Point sources of pollution} = \left[\left(\frac{\text{total point source nitrogen load} + \left(\text{total watershed area} \times 1.8 \text{ kg} \frac{\text{N}}{\text{ha}} \right)}{\text{total watershed area} \times 1.8 \text{ kg} \frac{\text{N}}{\text{ha}}} \right) - 1 \right] \times 100$$

year), Urban Development = 6.7 kg N/ha/year (6.0 lb N/acre/year), and Forest = 1.8 kg N/ha/year (1.6 lb N/acre/year)). The percent increase in nitrogen loading relative to forest was calculated as the increase in the N loading due to other land uses in excess of the amount of N naturally found in a totally forested land cover, i.e., a landscape that is totally forested would show no increase in N export over background input (1.8 kg N/ha).

The threshold separating **Somewhat Altered** from **Altered** conditions was defined as a 125% increase over the average nitrogen load contributed by forested land use, which is equivalent to about 4.0 kg N/ha/year (3.6 lb N/acre/year), the target nitrogen loading defined by water quality standards for the Neuse River basin (North Carolina) (NCAC, 2003) (Table 2). This threshold corresponds to an increase in nutrient loading that would be attained if 26% land cover were in agriculture or if 45% were in urban development. The equation used to measure the indicator is:

2.3.2.3. *Indicator 8: Concentrated sources of pollution.* This indicator evaluates the concentrated pollution sources from Concentrated Animal Feeding Operations (CAFOs) as an additional source of nutrient loads. Data were assembled on the number and kinds of animals (swine, cattle, poultry, and horses) raised at concentrated feeding operations in each watershed. Respective waste generation by type of animal was derived from published estimates of farm animal waste generation and waste concentrations (NCDA, 2005). The total amount of nitrogen generated per animal type per year (Table 3) was then multiplied by the number of each type of animal in the watershed. The same thresholds marking the transitions between condition categories for Indicator 6 (Land-use effects on nutrient loading) and 7 (Point sources of pollution) were applied to this indicator (Table 2). To determine the percent increase in potential nutrient loading due to concentrated sources relative to loading that would occur under a totally forested land use, the following equation was used:

Landuse effects on nutrient loading

$$= \left[\left(\frac{(\text{ha agriculture} \times 10.3 \text{ kg N/ha}) + (\text{ha urban} \times 6.7 \text{ kg N/ha}) + (\text{ha forested} \times 1.8 \text{ kg N/ha})}{\text{total watershed area} \times 1.8 \text{ kg N/ha}} \right) - 1 \right] \times 100$$

$$\text{Concentrated sources of pollution} = \left[\left(\frac{\text{total concentrated source N load} + (\text{total watershed area} \times 1.8 \text{ kg N/ha})}{\text{total watershed area} \times 1.8 \text{ kg N/ha}} \right) - 1 \right] \times 100$$

2.3.2.2. *Indicator 7: Point sources of pollution.* This indicator incorporates the effects of the total annual export of nitrogen from a watershed from all National Pollution Discharge Elimination

¹ Not included in this protocol, but potentially useful for evaluating this indicator, would be the inclusion of septic tanks, landfills, and land application of sludge from publically owned treatment facilities.

Table 2
Sources and application of data used as metrics for coastal assessment indicators.

Indicator group	Indicator name	Data layer	Source of data	Application	Rationale
Hydrologic Regime Indicators					
1a,1b.	Riparian-channel condition	Field data collection required	Application of Riparian Assessment Procedure 2.0 (Rheinhardt et al. 2007b)	Determine average condition of stream network and riparian zones of contribution watershed.	The contributing watershed determines the quality and quantity of water supplied to its receiving estuary and provides habitat for anadromous species.
2.	Extent of ditching (% ditching)	(1) LiDAR (Light Detection and Ranging) data (2) USGS 1:24K hydrography maps and ground truthing	(1) NCDENR: Division of Emergency Management, Floodplain Mapping Program http://www.ncfloodmaps.com/ (2) USGS: http://nhd.usgs.gov/index.html	(1) Delineate watershed boundary (2) Determine length of ditches and streams	Ditches reduce residence time of water in watersheds and prevent pollutants from being processed in riparian zones before entering streams (Brown 1988).
3.	Wetland conversion (%)	(1) County soil surveys (2) Division of Coastal Management (DCM) wetland type maps	(1) NRCS Soil Survey Geographic Database (SSURGO) http://soils.usda.gov/survey/geography/ssurgo/ (2) NCDCM: Division of Coastal Management http://dcm2.enr.state.nc.us/wetlands/download.htm	(1) Map area of hydric soils (2) Identify wetland locations and areas	Wetlands increase residence time of water in a watershed and process pollutants (Johnston et al. 1990)
4.	Landuse effects on runoff (%)	(1) Current National land cover dataset (2) Division of Coastal Management (DCM) wetland type maps (3) Recent high resolution aerial photos	(1) NLCD: http://www.epa.gov/mrlc/nlcd-2006.html (2) NCDCM: http://dcm2.enr.state.nc.us/wetlands/download.htm (3) Google Earth http://www.google.com/earth/index.html	(1) Determine area for each landuse type (2) Delineate watershed boundary (3) Verify map data	Landuses vary in how they affect the quality, quantity, and velocity of stormwater runoff within a watershed.
5.	Watershed impervious area (%)	(1) National land cover data from urban imperviousness (2) Digital DOQQs (3) Recent high resolution aerial photos	(1) NLCD: http://www.epa.gov/mrlc/nlcd-2006.html (2) NC State University library DOQQs http://www.lib.ncsu.edu/gis/doqq.html (3) Google Earth http://www.google.com/earth/index.html	(1) Determine area of impervious areas (2) Check accuracy with DOQQs (3) Verify map data	Impervious surfaces greatly increase the quantity and velocity of stormwater runoff within a watershed (Schueler 1994).
Materials Flux/Pollution Indicators					
6.	Landuse effect on nutrient loading	(1) National land cover data (2) LiDAR (Light Detection and Ranging) data for delineating watershed boundaries	(1) NLCD: http://www.epa.gov/mrlc/nlcd-2006.html (2) NC State University library DOQQs http://www.lib.ncsu.edu/gis/doqq.html (3) Google Earth http://www.google.com/earth/index.html	(1) Determine area of impervious areas (2) Check accuracy with DOQQs (3) Verify map data	Non-forest land cover increases nutrient export in a watershed, leading to eutrophication in the receiving estuary.
7.	Point sources of pollution	National Pollutant Discharge Elimination System permits in past 12 months	BasinPro Million Acre Edition http://www.lib.unc.edu/reference/gis/datafinder/index.html?individual_data_layer_details=1&data_layer_id=3353	Identify point source pollution input to stream network and estuary	Point source pollution increases nutrient concentration of water exported to a receiving estuary (Beaulac and Reckho 1982), leading to increased eutrophication.
8.	Concentrated sources of pollution	List of active permits for Confined animal feeding operations (CAFOs)	NCDENR Aquifer Protection Section CAFO data http://portal.ncdenr.org/c/journal/view_article_content?groupId=38364&articleId=226971&version=1.0	Identify the number and kinds of animals (swine, cattle, poultry, horses) in each subwatershed.	Concentrated sources of pollution increases concentration of water exported to a receiving estuary, leading to increased eutrophication.
Aquatic Habitat Indicators					
9.	Nearshore Pollution	(1) National land cover data (2) Shellfish closure maps (3) Shoreline survey (4) Recent high resolution aerial photos	(1) NLCD http://seamless.usgs.gov/imperv.php (2) E-4 Sanitary Survey Report http://portal.ncdenr.org/web/mf/shellfish-closure-maps (3) NCDCM: http://dcm2.enr.state.nc.us/Maps/chdownload.htm (4) Google Earth http://www.google.com/earth/index.html	Identify potential sources of pollution in and near an estuaries shoreline using amount of impervious surface near estuarine shoreline and the density of boats in the estuary.	Highly developed areas along shorelines and marinas pollute estuaries.
10.	Shellfish closures	Shellfish closure maps	E-4 Sanitary Survey Report http://portal.ncdenr.org/web/mf/shellfish-closure-maps	Shellfish classifications: potential pollution sources including marinas, subdivisions, etc.	Shellfish closures indicate polluted waters, which degrade aquatic habitats.
11a.	Eutrophication (%)	(1) NCDWQ water quality monitoring (2) EPA 303d list	(1) NCDWQ http://portal.ncdenr.org/web/wq/ps/bpu (2) EPA 303d report http://portal.ncdenr.org/web/wq/ps/mtu/assessment	Quantify degree of eutrophication using surrogate metrics: chl a, DO, fish kills, and algal blooms.	Eutrophication degrades aquatic habitat and stresses aquatic organisms.

11b. Water quality (toxicants, %)	Quantify toxic pollutant concentrations in estuary using measurements in water, sediment, and fish tissue.	EPA 303d report http://portal.ncdenr.org/web/wq/ps/mtu/assessment PCB advisories http://epi.publichealth.nc.gov/fish/current.html	Toxic compounds degrade aquatic habitats and stresses and kills aquatic organisms.
12. Water column transparency (%)	Water clarity is an indicator of eutrophication (due to algal blooms) and excessive sedimentation. Locate potential barriers to fish migrations.	(1) NCDWQ http://portal.ncdenr.org/web/wq/ps/bpu/mtu/assessment (2) EPA 303d report http://portal.ncdenr.org/web/wq/ps/	Reduced light penetration stresses and kills SAV beds, thus degrading aquatic nursery areas.
13. Impediments to anadromous fish passage (%)	Stream network data road network data, and field reconnaissance	(1) USGS 1:24,000-scale hydrography data layer http://www.ncdot.org/it/gis/DataDistribution/DOITData/ (2) Integrated Statewide Road Network (ISRN) http://www.lib.unc.edu/reference/gis/datafinder/index.html?individual_dataset_details=1&data_set_id=395	River herring avoid passage through small culverts and low bridges during days of low light (Moser and Terra 1999).
14. Impediments to tidal circulation (%)	Shoreline survey Recent high resolution aerial photos	(1) NCDM: http://dcm2.emr.state.nc.us/Maps/chdownload.htm (2) Google Earth http://www.google.com/earth/index.html	Shoreline alterations (e.g., riprap, bulkheads) are correlated with reduced fish community integrity (Bilkovic and Roggero 2008).
15. Maintained channels, trawl areas, and SAV scars in submerged aquatic vegetation (SAV) beds (% SAV habitat unaffected)	Trawl zone maps Channel dredge maps Recent high resolution aerial photos	(1) NCDMF http://portal.ncdenr.org/web/mf/maps-to-view-and-print (2) U.S. Army Corps of Engineers (3) Google Earth http://www.google.com/earth/index.html	Predatory nekton depend on seagrass communities and are reduced when mechanical scars cover >27% of SAV habitat (Burfeind and Stunz 2005). Mechanical oyster harvesting also degrades benthic habitats (Lenihan and Peterson 2004).

Table 3

Estimate of nitrogen loading by concentrated animal feeding operations, by type of animal.

Animal	Waste generated per animal (Mg/year)	Waste nitrogen concentration (kg/Mg)	Nitrogen generated per animal (kg N/year)
Swine	1.72	6.15	0.280
Poultry	0.19	13.20	0.014
Cattle	13.61	6.00	2.268
Horse	8.35	6.05	1.380

2.3.3. Aquatic habitat indicators

Seven indicators characterize the extent to which aquatic habitat has been altered in the receiving estuary and along stream networks used by anadromous fish (Table 2). Aquatic habitat indicators focus on the magnitude of habitat degradation relative to an unaltered estuary. Some indicators focus on habitat pollution, while others focus on physical alterations to habitat.

2.3.3.1. Indicator 9: Near-shore pollution. This indicator evaluates the contribution of potential sources of nearshore pollution to the receiving subestuary, i.e., all potential sources within 0.4 km (0.25 miles) landward of the mapped shoreline (Table 2). The most likely nearshore land uses that negatively impact estuarine habitat condition are commercial marinas and impervious surfaces.

Marina facilities have the potential to pollute shellfish habitat. Utilizing the presence of marinas and marina boat slips is consistent with rationale used by the North Carolina Division of Marine Fisheries (NCDMF) Shellfish Sanitation Section to close shellfish harvesting in waters adjacent to marinas. All waters enclosed by a marina (i.e., more than 10 boats, *sensu* 15A NCAC 18A 0.0901) are classified as *Prohibited* for the harvesting of shellfish, and an additional area beyond the marina may also be classified as *Prohibited*, depending on the number of boat slips the marina supports.

Percent impervious surface was determined by the National Land Cover Dataset (NLCD) Urban imperviousness database. Methods for acquiring imperviousness data were the same as those described for Indicator #6, except that only land within 0.4 km inland from the mapped shoreline was considered.

Condition was determined by the lowest scoring metric, determined by the either percent impervious surface in the nearshore (0.4 km) zone or the number of marina boat slips per length of shoreline. Thresholds for the **Relatively Unaltered** and **Somewhat Altered** categories for percent impervious surface were more stringent than those used for the “Watershed impervious area” indicator (Indicator #5, Table 2) due to the close proximity (0.4 km) of impervious surface to the receiving estuary. If marinas are present, the number of boats slips is divided by shoreline length with 1–6 boats slips per km of shoreline (1–10/mile) defining the **Altered** condition. The lowest score of equations a and b are used to measure the indicator:

$$(a) \text{ Nearshore pollution} = \left(\frac{\text{total number of marina boat slips}}{\text{km of shoreline}} \right)$$

$$(b) \text{ Nearshore pollution} = \% \text{ impervious surface within 0.4 km of shoreline}$$

2.3.3.2. Indicator 10: Shellfish closures. This indicator evaluates the relative area of Shellfish Classified Waters within a receiving estuary that is either temporarily or permanently closed to harvesting. Closures of shellfish beds may be due to land-based sources of nutrients and contaminants, discharges from wastewater treatment facilities, or nearby marinas. Consequently, this indicator integrates several potentially overlapping sources of nutrient degradation as well as indicating the condition of habitat used by

other aquatic species. This indicator is one that resource managers and the public readily understand.

Shellfish closure classifications, according to North Carolina Administrative Code, are: (1) Conditionally Approved, but Closed, i.e., normally closed but temporarily open when weather conditions are favorable (generally based on rainfall amounts within a 24 h period) and (2) Prohibited, i.e., unsuitable for the harvesting of shellfish at any time. In North Carolina, current Shellfish Growing Area Closure maps that identify Conditionally Approved and Prohibited areas are revised every three years by the NCDMF.

Utilizing shellfish closure data and maps, estimates were made of the total acres of Shellfish Classified Waters, area of Conditionally Approved, Closed waters, and area of Prohibited waters within the receiving subestuary. It was assumed that shellfish habitat is degraded when shellfish beds are periodically or permanently closed to harvest due to pollution. The percentage of area closed was used to designate habitat condition for a subestuary, with **Severely Altered** defined as >50% of the shellfish classified waters being closed (Table 2). The other condition category thresholds were arbitrarily chosen. The equation used to measure the indicator is:

$$\text{Shellfish closures (\%)} = \left(\frac{\text{area Conditionally Approved, Closed} + \text{area Prohibited}}{\text{total area of all Shellfish Classified waters}} \right) \times 100$$

2.3.3.3. *Indicator 11: Water quality indicators.* Two components of water quality are used to indicate condition: (1) degree of eutrophication based on levels of chlorophyll *a* (chl *a*) or dissolved

Water quality (eutrophication, %)

$$= \left(\frac{\# \text{ samples that exceed DO threshold levels} + (\# \text{ samples that exceed chl } a \text{ threshold levels})}{\text{total number of water samples}} \right) \times 100$$

oxygen (DO), and (2) toxicants present in water, sediment, and fish. The application of these indicators requires a water quality monitoring program of sufficient duration and intensity to evaluate the frequency in which water samples exceed concentrations established as safe by the U.S. Environmental Protection Agency (USEPA). North Carolina has a Nutrient Sensitive Water classification, which is applied to large areas of estuaries and stream reaches, based on the USEPA 303d criteria established for impaired water bodies (USEPA 303d). We used these water quality standards as a basis for developing thresholds for each component of water quality measured within both watersheds and subestuaries. Unfortunately, many subestuaries in North Carolina lack monitoring programs for eutrophication or toxicants. This is also likely to be the case for most subestuaries elsewhere. Nonetheless, we present examples of metrics that could be used in watersheds where monitoring data are available and how such data were calibrated for North Carolina subestuaries.

2.3.3.3.1. *Indicator 11a: Eutrophication.* This indicator evaluates chl *a*, DO, frequency of fish kills, and algal blooms to quantify degree of eutrophication. Water quality data are obtained from the latest 5-year-long North Carolina Division of Water Quality (NCDWQ) monitoring periods used to identify USEPA 303d list of impaired

waters (USEPA 303d List). Streams in a watershed and its receiving subestuary are scored separately. If both DO and chl *a* exceed threshold levels for a water sample, to prevent double counting only the water quality data providing the lowest score are used. The percent of threshold exceedances is calculated by dividing the total number of samples in which concentrations are higher than established threshold levels by the total number of samples collected, and multiplying by 100. Where both DO and chl *a* data are sampled at the same time and location, then only the datum that provides the lowest score is used.

The criteria used by NCDWQ to define water quality were used to separate condition categories (Table 2). The “Impaired” waters designation was used to define the threshold between the **Some-what Altered** and **Altered** conditions. Impairment was defined by NCDWQ as >10% of samples exceeding USEPA water quality thresholds during the last NCDWQ basin-wide 5-year monitoring cycle used to prepare water quality management plans. The USEPA 303d list defining Nutrient Sensitive Water was included as a criterion for the threshold between the **Altered** and **Severely Altered** conditions. At least one “major” pollution events (defined

as a significant algal bloom or fish kill) within the last two 5-year monitoring cycles was used to define the **Severely Altered** threshold. The equation used to measure the indicator is:

2.3.3.3.2. *Indicator 11b (1–3): Toxicants.* This indicator evaluates the threshold levels of cationic metals and organic toxicants in (1) the water column, (2) in sediment, and (3) in fish tissue from samples taken from a stream network and its receiving subestuary (Table 2). Toxicity samples, toxicity advisories, and USEPA 303d toxicity listings are all used to quantify the indicator. Toxicity data from water samples, sediment samples, and fish tissue samples are used to calculate a single toxicant value for each sample, by incorporating the most conservative metric, i.e., the metric that would score lowest. If a given sample is tested for multiple toxicants and more than one measure exceeds its threshold level, to prevent double counting only the lowest scoring measure is used in the calculations.

The following toxicity data are used to measure the toxicant indicator within a stream network and its receiving subestuary:

1. Monitoring data results (cationic metals and organic toxicants) from water and sediment samples collected during the latest 5-year monitoring period.
2. Results from aggregate aquatic toxicity tests and aggregate sediment toxicity tests collected within the latest two 5-year monitoring periods.

3. Monitoring data results for mercury in fish tissue collected within the latest two 5-year monitoring periods.
4. USEPA 303d toxicant listings for mercury.
5. Advisories for PCB and/or dioxins or its metabolites collected within the latest two 5-year monitoring periods.

As with the eutrophication indicator (11a), data from the NCDWQ latest 5-year monitoring cycles were used to establish condition thresholds for this indicator, e.g., the **Altered** condition was defined by >20% of water samples exceeding the threshold level during the last 5-year monitoring cycle or the occurrence of at least one “major” exceedance event during the two 5-year monitoring cycles (Table 2). The equation used to measure the indicator is:

$$\text{Water quality (toxicants, \%)} = \left(\frac{\# \text{ samples that exceed toxicity threshold levels}}{\text{total number of water samples}} \right) \times 100$$

2.3.3.3.3. *Indicator 12: Water column transparency.* This indicator evaluates the turbidity of streams in a network and in the stream network’s receiving estuarine waters. For North Carolina,

$$\text{Impediments to anadromous fish passage (\%)} = \left(\frac{\text{tributary length upstream of obstructions}}{\text{total stream network length}} \right) \times 100$$

we used the NCDWQ threshold of 25 nephelometric turbidity units (NTUs) for estuarine waters and 50 NTUs for streams. All bodies of water classified as “S waters” (saline designation) are considered estuarine for turbidity measurements (*sensu* NCDWQ, 2010). The latest 5-year NCDWQ monitoring cycle was used to evaluate the indicator.

Current water quality standards employed by NCDWQ to define “impaired waters” was used to determine the threshold level separating the **Altered** from the **Somewhat Altered** condition categories (Table 2), i.e., >10% of water quality samples exceeding water transparency thresholds (defined above) during the latest NCDWQ 5-y monitoring cycle. Other condition category thresholds were arbitrarily chosen. The equation used to measure the indicator is:

$$\text{Water column transparency (\%)} = \left(\frac{\# \text{ samples that exceed NTU threshold levels}}{\text{total number of samples}} \right) \times 100$$

2.3.3.4. *Indicator 13: Impediments to anadromous fish passage.* This indicator evaluates impediments to the passage of anadromous fish to spawning areas and should only be used where passage has been available historically. Structures that are potentially impassable to fish include dams and pipe culverts. However,

$$\text{Impediments to tidal circulation (\%)} = \left(\frac{\text{length of bulkheads} + \text{length of filled wetlands}}{\text{total length of original, natural shoreline}} \right) \times 100$$

not all culverts and bridges are considered to be impediments. Based on data of Moser and Terra (1999), impediments were defined as only culverts smaller than 3.65 m (12 ft) in diameter and bridges elevated less than 1 m above the stream surface. Obstructions are assumed where primary or secondary roads cross tributary streams.

Within each watershed, the length of tributary streams (1st to 3rd order) upstream of culverts and dams was divided by the total length of tributary streams in the watershed to give the percent of the stream network inaccessible to anadromous fish (Table 2). The **Severely Altered** condition was defined as >25% of the stream network being restricted to fish passage. A culvert or dam present in ≥ 4 th order streams of a network provides a zero

score for the indicator because the obstruction would deny fish access to all the lower order tributaries. The equation used to measure the indicator is:

2.3.3.5. *Indicator 14: Impediments to tidal circulation.* This indicator evaluates impediments to circulation in estuarine waters by characterizing the extent to which tidal flow/mixing has been altered. The primary alterations to circulation are bulkheads and rip-rap along shorelines and fill for road crossings, bridges, causeways, and spoil disposal sites. In North Carolina, the various types of coastal structures are specifically defined and regulated by the North Carolina Division of Coastal Management (NCDWM).

To calculate the metric, the length of original shoreline and length of coastal wetlands altered by coastal structures are estimated using high resolution aerial photographs and shoreline surveys. The percent of impacted shoreline is calculated by summing the length of shoreline impacted by structures and

dividing this value by the length of original, un-impacted shoreline (Table 2). Length criteria defining condition category thresholds are the same ranges applied to impediments to anadromous fish migration (Indicator 13). The equation used to measure the indicator is:

2.3.3.6. *Indicator 15: Maintained channels, trawl areas, and SAV scars in submerged aquatic vegetation (SAV) habitat.* Alterations to estuarine substrate reduce the ecological integrity of benthic communities and SAV beds. Alterations include dredging channels, bottom trawling, and gouging seagrass beds with boat propellers (scarring). Predatory nekton dependent on seagrass communities are also affected by such alterations, but only at relatively high levels of scarring (>27%) (Burfeind and Stunz, 2005).

In North Carolina, areas historically altered by trawling are inferred from maps of areas prohibited from shrimp trawling, available from the Division of Marine Fisheries (NCDMF). Maps of dredged shipping channels are accessible from the U.S. Army Corps of Engineers (USACE). Oyster harvesting areas (oyster dredging) may be included if data are available. High resolution aerial photography can reveal the presence of scarred seagrass beds resulting from trawling and prop damage.

The percent of SAV habitat is calculated separately from non-SAV habitat because of the special importance of SAV beds to the life cycle of important commercial fishery species (e.g., bay scallops). The score for bottom condition is the lower score any of the various habitat condition indicators if more than one metric is measured in the same receiving estuary. The work of Burfeind and Stunz (2005) was used as the basis for setting the threshold for **Severely Altered** condition, i.e., $\geq 25\%$ of SAV habitat altered (Table 2). The lowest scoring of equations a and b should be used to measure the indicator:

(a) Maintained channels and trawl areas not in SAV habitat (% benthic habitat unaffected)

$$= \left(\frac{\text{area unaffected by trawling and navigation channel maintenance}}{\text{total area of receiving subestuary}} \right) \times 100$$

(b) Maintained channels, trawl areas, and SAV scars, within SAV habitat (% SAV habitat unaffected)

$$= \left(\frac{\text{area of SAV habitat not altered by trawling, channels, or prop scars}}{\text{total area of SAV habitat, including altered areas}} \right) \times 100$$

2.4. Application of data

The RWA protocol was applied to one watershed and subestuary to illustrate how the indicators can be used and interpreted. Then RWA data was used to compare that watershed with other (nearby) coastal watersheds. All watersheds being compared are primarily in an agricultural setting, but they differ in condition relative to channel and riparian zones of contributing streams, nutrient loading resulting from landuse differences (agricultural vs. forest), number of boats slips supported, extent of shellfish closures, and proximity to dredged estuarine channels.

3. Results

3.1. Watershed description and RWA results

The Eastman Creek watershed (Fig. 1) is located in Carteret County, North Carolina, about 8 km north of Beaufort, North Carolina. The watershed covers 650 ha, has 2 km of streams and 14 km of shoreline. Indicator scores for the Eastman Creek drainage and Core Creek subestuary are provided in Table 4. Eight of the 11 indicators for which there were data available, scored as either **Altered** ($n = 4$) or **Severely Altered** ($n = 4$).

A stream network condition assessment (*sensu* Rheinhardt et al., 2007b) was conducted at two locations in the Eastman Creek drainage network. Although riparian and channel data from more reaches would be needed to more thoroughly characterize the

condition of the stream network, the limited data indicate that natural vegetative cover had been reduced in riparian zones (conversion of natural forest to cropland or managed monoculture forest) and that connectivity between channels and floodplain had been altered by channelization (in both silvicultural and agricultural stream reaches). As a result, channel and riparian zone condition (Indicators #1a and b) both scored as **Altered** (score = 46 and 52, respectively) due to channel modifications and alterations to riparian habitats.

The watershed was extensively ditched for agriculture and silviculture, leaving 5.5 km of natural streams and 5.7 km of ditches in the watershed. Thus, more than 50% of the total drainage network was composed of ditches. As a consequence, Indicator #2 scored as **Severely Altered**. Ditches were presumably constructed to drain wetlands in order to convert forest land use to agriculture. Ninety-five percent of the drainage basin (650 ha) consisted of hydric soils (617 ha), but only 44% (271 ha) of hydric soils still supported wetlands. As a result, Indicator #3 scored as **Altered**.

Sixty-three percent of the drainage basin was forest or managed for pine silviculture (410 ha), while agricultural land use occupied 20% of the basin and residential and urban land uses occupied the remaining 17%. As a consequence, Indicator #4 scored as **Severely Altered**.

Most commercial and residential development was concentrated in the lower third of the drainage basin and included one residential subdivision and two marinas. However, impervious

surfaces covered only 2.1% of the watershed. As a result, Indicator #5 scored **Relatively Unaltered**.

More than one third of the watershed was converted from forest to agricultural or suburban land uses, both of which have the potential to contribute excess nutrients to the receiving estuary.

Thus, Indicator #6 was scored as **Altered**. There were no data available for dissolved oxygen (DO), turbidity, water transparency, or toxic contamination of water, sediment, or fish in the Eastman Creek network or the receiving Core Creek subestuary.

There were no National Pollutant Discharge Elimination System (NPDES) permitted discharges, no concentrated animal feeding operations (CAFOs), nor any other point source or other concentrated sources of pollution in the drainage basin. Therefore, neither the Eastman Creek drainage nor the Core Creek subestuary had any known point sources of pollution (Indicator #7) or concentrated sources of pollution in the watershed (Indicator #8). There were two on-site, non-discharge wastewater treatment facilities in the basin, but non-discharge waste treatment facilities are not included as an indicator. Thus, both indicators scored as **Relatively Unaltered** from those perspectives.

The Core Creek subestuary had two marinas containing a total of 28 boat slips along 14 km of natural, original shoreline (2 slips/km) and 2.1% of the nearshore zone was impervious surfaces. Both metrics for Indicator #9, impervious surface and boat density, scored 89, which was **Somewhat Altered**.

All shellfish beds in Core Creek were closed due to fecal coliform contamination, likely due to runoff from agricultural, residential,

Table 4

Indicator scores for Eastman creek watershed (650 ha). The best (maximum) score is 100, indicating relatively unaltered condition. NDA = no data available.

Indicator name	Raw metric	Indicator score (indexed 0–100)	Condition category
Hydrologic regime			
1a Riparian-stream condition (riparian zone score)	46	46	Altered
1b Riparian-stream condition (stream channel score)	52	52	Altered
2 Extent of ditching (km ditches/km streams)	104	0	Severely altered
3 Wetland conversion	44	37	Altered
4 Land-use effects on runoff	37	28	Severely altered
5 Watershed impervious area	2.1	97	Relatively unaltered
Materials/flux pollution			
6 Land-use effects of nutrient loading	140	53	Altered
7 Point sources of pollution	0	100	Relatively unaltered
8 Concentrated sources of pollution	0	100	Relatively unaltered
Aquatic habitat			
9 Near-shore pollution (boat slips/km = 28/14)	2	89	Somewhat Altered
10 Shellfish closures	100	0	Severely altered
11a Water quality – eutrophication	NDA	NDA	NDA
11b Water quality	NDA	NDA	NDA
12 Water column transparency	NDA	NDA	NDA
13 Impediments to anadromous fish migration	NDA	NDA	NDA
14 Impediments to tidal circulation	3.2	93	Relatively unaltered
15 Maintained channels, trawl areas, SAV scars	100	0	Severely altered

and urban land uses, the two marinas present in the subestuary, and loss of more than half of the original wetlands. Thus, this habitat quality indicator (#10) scored zero (**Severely Altered**).

There were no water quality data available to characterize the degree of eutrophication (Indicator #11a), the presence of contaminants in water, sediments, or fish tissues (Indicator #11b), or water column turbidity (Indicator #12). Therefore, these indicators could not be used to evaluate aquatic habitat.

None of the small streams in the Eastman Creek drainage were designated by the NCDMF as historic spawning areas for anadromous fish, and so Indicator #13 was not applicable. Bulkheads and shoreline/wetland fill comprised 3.2% of the shoreline, primarily associated with the two marinas. Thus, there were few impediments to tidal circulation (Indicator #14) and so this habitat quality indicator scored as **Relatively Unaltered**.

There was no current or historic documentation regarding the distribution of submerged aquatic vegetation (SAV) or information on trawl fishing activity. However, trawling was unlikely in the Core Creek subestuary because it is narrow and bisected lengthwise by the Intracoastal Waterway (ICW), which is a busy navigation channel. The effect of dredging to maintain the ICW was assumed to extend 100 m (300 ft) from the channel center. Thus, due to the narrowness of Core Creek, dredging maintenance of the ICW was assumed to negatively impact 100% of the benthic habitat in the subestuary. This meant that benthic habitat integrity (Indicator #15) was **Severely Altered**.

The conversion of forest land to agricultural and urban land uses in the Eastman contributing watershed has resulted in increased eutrophication and dredging has severely altered benthic habitat. The RWA results highlight these problems and shows where ecological improvements can and can't be made in the Eastman

Creek basin. However, other small coastal watersheds also contribute to the condition of the Core Creek estuary (see next section).

3.2. Comparison among coastal watersheds

The RWA was also conducted on four additional watersheds located close to Eastman Creek, and all emptying into the Core Creek subestuary (Fig. 1). The assessment of these watersheds showed that the five subwatersheds (Eastman Creek included) were similar in condition with respect to hydrologic regime and material/flux pollution (Table 5), not surprising considering their land use is similar. Most variation among sites was due to differences in aquatic habitat condition. For example, even though the Russell Creek watershed showed the worst condition for "Nearshore pollution" (due to its higher density of boat slips per length of shoreline), it had a lower proportion of area closed to shell fishing than the other subestuaries, presumably because it received more tidal flushing due to its proximity to the Newport River estuary (Fig. 1). Further, Russell Creek only had 52% of its bottom impacted by dredging associated with maintaining the ICW, while the benthic zone of Eastman, Bell, and North Ware creeks were determined to be 100% impacted by the ICW. South Ware Creek was **Relatively Unaltered** with respect to dredging, trawl damage, SAV damage, probably because it was a small estuary located more than 100 m from the ICW.

4. Discussion

The RWA framework is considered rapid relative to similar approaches for identifying sources of problems in estuaries. Most of the assessment can be accomplished using data sources accessible on the web. The exception is that information on stream network condition requires collecting field data, but even those data can be obtained rapidly. Although the indicators for this study were calibrated for conditions typically found in coastal North Carolina, they could be scaled differently for other geographic regions or incorporate other types of locally available data. For example, arid regions have mostly episodic runoff and many differ in landuses relative to the coastal landuses and climate described in this study. Even so, the general framework presented here is transferrable to other regions where climate, landuse, and data for contributing watersheds and receiving estuaries might differ.

The types and availability of data change frequently and so the RWA approach was designed to remain flexible enough to accommodate new data sources. In North Carolina, private docks and boat slips not associated with marinas are prevalent along shorelines, but there were no readily available data bases regarding these. Likewise, data on non-discharge land application of treated waste waters, near-shore pollution from landfills, septic tanks and their drain fields, and stormwater outfalls are not yet available, but could be incorporated into the RWA protocol once they are. Thus, not only is the RWA approach flexible enough to incorporate new data, it is also useful for helping identify where data gaps exist.

The main benefit of the RWA approach is that it provides coastal resource managers with a method for comparing the general condition of contributing watersheds and receiving subestuaries, identifying problems in need of attention, and prioritizing watershed-wide strategies for improving or enhancing current conditions. Although the RWA approach would be useful for identifying general types of improvements needed in watersheds, it is not appropriate to use the RWA indicators to identify the exact location or design of site-specific restoration projects or Best Management Practices (BMPs). Further, the indicators are not expected to have the resolution to differentiate between watershed or subestuarine condition before and after restoration has taken place. That is, the legacy effects of ~200 years of altered landscapes and water quality

Table 5
Summary of indicator scores for five adjacent watersheds in the Core creek subestuary. Score 0–29 = severely altered (SA), 30–59 = altered (A), 60–89 = Somewhat altered (SoA), 90–100 = relatively unaltered (RU). NDA = no data available. For additional information, spatial information on condition and characteristics of study watersheds are overlaid on watershed maps in Chapter 4 of base report (ECU and ED, 2006).

Watershed	Eastman	Bell	North ware	South ware	Russell
Watershed area (ha)	650.3	357.3	94.3	110.5	339.9
Stream length (km)	2.0	2.3	0.8	0.4	1.5
Shoreline length (km)	14.1	6.0	0.0	1.4	1.9
Hydrologic regime					
1a Riparian zone condition	A	SA	SA	A	A
	46	28	13	34	56
1b Channel condition	A	SA	SA	SA	A
	52	28	6	8	39
2 Extent of ditching	SA	SA	SA	SA	A
	0	0	0	0	51
3 Wetland conversion	A	A	A	A	A
	37	32	26	31	23
4 Land-use effects on runoff	A	A	A	A	A
	28	25	21	23	19
5 Watershed impervious area	RU	RU	RU	RU	RU
	97	97	98	98	96
Materials/flux pollution					
6 Land-use effects of nutrient loading	A	A	SA	A	SA
	53	39	25	35	18
7 Point source pollution	RU	RU	RU	RU	RU
	100	100	100	100	100
8 Concentrated sources of pollution	RU	RU	RU	RU	RU
	100	100	100	100	100
Aquatic habitat					
9 Near-shore pollution in estuary	SoA	RU	RU	SoA	SA
	89	99	99	87	0
10 Shellfish closures in estuary	SA	SA	SA	SA	SoA
	0	14	0	0	68
11a Water quality - eutrophication	NDA	NDA	NDA	NDA	NDA
11b Water quality - toxicants	NDA	NDA	NDA	NDA	NDA
12 Water column transparency	NDA	NDA	NDA	NDA	NDA
13 Impediments to anadromous fish migration	NDA	NDA	NDA	NDA	NDA
14 Impediments to circulation	RU	RU	RU	RU	RU
	93	96	98	99	95
15 Maintained channels, trawl areas, SAV scars	SA	SA	SA	RU	A
	0	0	0	100	52

changes are unlikely to be detectable following a single restoration, unless the restoration is conducted on a large scale. In addition, given that data for several indicators are closely associated and potentially redundant, (e.g., boat slip density and shellfish closures or land use and nutrient loading), scores for indicators shouldn't be combined to provide an integrated score without application of some type of weighting (which would require further justification).

Another limitation of the protocol is the lack of data for some indicators, especially for water quality constituents. In this study, water quality data on eutrophication, toxicants, and water column transparency were not available in spite of NCDWQ having a fairly robust, state-wide monitoring program. The main problem is the lack of congruence between the location of small watersheds and established monitoring stations with repeated sampling over several years. In contrast, shellfish closure and marina data information are readily available for most coastal waters, in North Carolina and in most other developed areas of the world.

Threshold values separating condition categories for some indicators were based on scientific data (where available) and state and federal water quality standards, but for some variables, threshold values were arbitrarily defined based on best professional judgment (BPJ). Thresholds that rely on BPJ can be used to highlight where data gaps exist and hopefully encourage additional research and monitoring. For other coastal regions, thresholds (and indicators) can be based on regional differences and local data availability.

Traditional mitigation opportunities are limited in many coastal watersheds (including North Carolina) because in-kind restoration opportunities are generally not available, or if available, do not adequately address the main causes of coastal habitat degradation. In addition, some degradations are not even recognized as impairments in need of mitigation. For example, shoreline stabilization structures are not currently considered to be a source of impairment in North Carolina even though they are known to lead to degradation and loss of shallow-water nursery habitats. As a result, compensatory mitigation is not required when shorelines are hardened (stabilized with structures), nor is the restoration/removal of shore stabilization structures currently considered to be legally acceptable as compensatory mitigation. A regionally explicit RWA protocol could provide policy makers with justification to revise resource conservation laws and compensatory mitigation policy to reflect more current understanding of the relationships between estuarine health and the specific aspects of contributing watersheds and receiving estuaries.

5. Conclusions

The RWA framework provides coastal resource managers with an approach for comparing the condition of small coastal watersheds and receiving subestuaries, for specifying problems in need of attention, and for prioritizing watershed-wide strategies for improving or enhancing conditions. Using mostly web-accessible data bases, the framework is rapid and adaptable to regionally-

specific conditions and data bases. Because the RWA framework links problems with specific indicators of coastal watershed condition, the approach can provide support for resource policies that tie improved indicator condition to compensatory mitigation strategies.

Conflict of interest

None of the authors has any actual or potential conflict of interest, including any financial, personal, or other relationships with other people or organizations that could inappropriately influence, or be perceived to influence, this manuscript. R. D. Rheinhardt.

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Appendix. Abbreviations used in manuscript

CAFO	Concentrated Animal Feeding Operation
DO	Dissolved oxygen
ECU	East Carolina University
ED	Environmental Defense
HGM	Hydrogeomorphic
IBI	Index of biological integrity
ICW	Intercoastal waterway
MEA	Millennium Ecosystem Assessment
NCDA	North Carolina Department of Agriculture
NCDCM	North Carolina Division of Coastal Management
NCDMF	North Carolina Division of Marine Fisheries
NCDENR	North Carolina Department of Environment and Natural Resources
NCDWQ	North Carolina Division of Water Quality
NLCD	National Land Cover Dataset
NPDES	National Pollution Discharge Elimination System
NGO	non-governmental organizations
NPDES	National pollution
NTU	Nephelometric turbidity units
PCB	Polychlorinated biphenyl
RWA	Rapid watershed assessment
SAV	Submerged aquatic vegetation
TMDL	Total Maximum Daily Load
USACE	United States Army Corps of Engineers
USEPA	United States Environmental Protection Agency
USFWS	United States Fish and Wildlife Service

Rural Low Order Riparian Assessment

Indicator	Condition Category			
	Relatively Unaltered	Somewhat Altered	Altered	Severely Altered
1a. Riparian-stream condition (riparian zone)	Composite score for riparian zone is ≥ 90 .	Composite score for riparian zone is 60 to 89.	Composite score for riparian zone is 30 to 59.	Composite score for riparian zone is 0 to 29.
Score =	100 90	89 60	59 30	29 0
1b. Riparian-stream condition (stream channel)	Composite score for stream channel is ≥ 90 .	Composite score for stream channel is 60 to 89.	Composite score for stream channel is 30 to 59.	Composite score for stream channel is 0 to 29.
Score =	100 90	89 60	59 30	29 0
2. Extent of ditching	Ditching limited to roadsides and road crossings that, without drainage, would impede water flow and result in ponding.	Drainage from ditches is $\leq 10\%$ that from natural channels.	Drainage from ditches is $>10\%$ to 25% that from natural channels.	Drainage from ditches is $>25\%$ that from natural channels.
Score =	100 90	89 60	59 30	29 0
3. Wetland conversion	$\leq 5\%$ of wetlands are converted.	6% to 25% of wetlands are converted.	26% to 50% of wetlands are converted.	$>50\%$ of wetlands are converted.
Score =	100 90	89 60	59 30	29 0
4. Land-use effects on runoff	$<10\%$ of watershed is Urban Development and Agriculture.	10% to 19% of watershed is Urban Development and Agriculture.	20% to 34% of watershed is Urban Development and Agriculture.	$\geq 35\%$ of watershed is Urban Development and Agriculture.
Score =	100 90	89 60	59 30	29 0
5. Watershed impervious area	$<8\%$ is impervious area.	8% to 12 % is impervious area.	13% to 24% is impervious area.	$>24\%$ is impervious area.
Score =	100 90	89 60	59 30	29 0

Figure A.1 Condition thresholds related to hydrologic indicators.

Indicator	Condition Category			
	Relatively Unaltered	Somewhat Altered	Altered	Severely Altered
6. Land-use effects on nutrient loading	<50% increase in nutrient loading from Agriculture and Urban development (relative to forested cover)	50% to 124% increase in nutrient loading from Agriculture and Urban development (relative to forested cover)	125% to 199% increase in nutrient loading from Agriculture and Urban development (relative to forested cover)	≥ 200% increase in nutrient loading from Agriculture and Urban development (relative to forested cover)
Score =	100 90	89 60	59 30	29 0
7. Point sources of pollution	<50% increase in nutrient loading from point source pollution (relative to forested cover)	50% to 124% increase in nutrient loading from point source pollution (relative to forested cover)	125% to 199% increase in nutrient loading from point source pollution (relative to forested cover)	>200% increase in nutrient loading from point source pollution (relative to forested cover)
Score =	100 90	89 60	59 30	29 0
8. Concentrated sources of pollution	<50% increase in nutrient loading from concentrated sources of pollution (relative to forested cover)	50% to 124% increase in nutrient loading from concentrated sources of pollution (relative to forested cover)	125% to 199% increase in nutrient loading from concentrated sources of pollution (relative to forested cover)	>200% increase in nutrient loading from concentrated sources of pollution (relative to forested cover)
Score =	100 90	89 60	59 30	29 0

Figure A.2. Condition thresholds related to materials/flux pollution indicators.

Indicator	Condition Category							
	Relatively Unaltered		Somewhat Altered		Altered		Severely Altered	
9. Near-shore pollution	Impervious surfaces are <2% AND there are no marina ¹ boat slips in the receiving estuary.							
Score =	100	90	89	60	59	30	29	0
10. Shellfish closures	<10% of shellfish waters are Conditionally Approved (but closed) or Prohibited.							
Score =	100	90	89	60	59	30	29	0
11a. Water quality - eutrophication	<1% of all water samples taken during the last 5-y monitoring cycle exceed NCDWQ threshold levels ² for Chlorophyll a (Chl a) or dissolved oxygen (DO) AND no major exceedance event ³ has occurred within the last two 5-y monitoring cycles.							
Score =	100	90	89	60	59	30	29	0
11b1. Water quality - toxicants (in WATER)	<1% of all water samples taken during the last 5-y monitoring cycle exceed any NCDWQ toxicant threshold levels AND no major exceedance event has occurred within the last two 5-y monitoring cycles.							
Score =	100	90	89	60	59	30	29	0
11b2. Water quality - toxicants (in SEDIMENTS)	>1% of sediment samples taken within the last 5 y exceed any NOAA Sediment Quality Guidelines (Effects Range Median) AND no major exceedance event ³ within the last 10 y.							
Score =	100	90	89	60	59	30	29	0

Figure A.3. Condition thresholds related to aquatic habitat indicators.

11b3. Water quality - toxicants (in FISH TISSUE)	<1% of fish or shellfish tissue taken within the last two 5-y monitoring cycles contain mercury at or above the NCDWQ threshold level AND there has been no 303d listing for mercury AND there has not been an advisory issue for PCV or dioxin (TCDD) or its metabolites.	1% to 9% of fish or shellfish tissue taken within the last two 5-y monitoring cycles contain mercury at or above the NCDWQ threshold level AND there has been no 303d listing for mercury AND there has not been an advisory issue for PCV or dioxin (TCDD) or its metabolites.	10% to 19% of fish or shellfish tissue taken within the last two 5-y monitoring cycles contain mercury at or above the NCDWQ threshold level AND there has been no 303d listing for mercury AND there has not been an advisory issue for PCV or dioxin (TCDD) or its metabolites.	> 20% of fish or shellfish tissue taken within the last two 5-y monitoring cycles contain mercury at or above the NCDWQ threshold level OR there has been a 303d listing for mercury OR there has been an advisory issue for PCV or dioxin (TCDD) or its metabolites.
	Score =	100 90	89 60	59 30
12. Water column transparency	<1% of all turbidity tests conducted within the last 5-y monitoring cycle exceed threshold levels ⁵ defined as impaired waters by NCDENR.	1% to 9% of all turbidity tests conducted within the last 5-y monitoring cycle exceed threshold levels ⁵ .	10% to 19% of all turbidity tests conducted within the last 5-y monitoring cycle exceed threshold levels ⁵ .	>20% of all turbidity tests conducted within the last 5-y monitoring cycle exceed threshold levels ⁵ .
	Score =	100 90	89 60	59 30
13. Impediments to anadromous fish migration	<5% of tributary stream ⁶ length is altered by dams ⁷ or pipe culverts AND there are no dams ⁷ or pipe culverts in \geq 4th order streams ⁸ that feed the receiving estuary.	5% to 9% of tributary stream ⁶ length is altered by dams ⁷ or pipe culverts AND there are no dams or pipe culverts in \geq 4th order streams ⁸ that feed the receiving estuary.	10% to 24% of tributary stream ⁶ length is altered by dams ⁷ or pipe culverts AND there are no dams or pipe culverts in \geq 4th order streams ⁸ that feed the receiving estuary.	\geq 25% of tributary stream ⁶ length is altered by dams ⁷ or pipe culverts AND there are no dams or pipe culverts in \geq 4th order streams ⁸ that feed the receiving estuary.
	Score =	100 90	89 60	59 30
14. Impediments to tidal circulation	<5% of original shoreline length has been latered by coastal structures or by fill.	5% to 9% of original shoreline length has been latered by coastal structures or by fill.	10% to 24% of original shoreline length has been latered by coastal structures or by fill.	\geq 25% of original shoreline length has been latered by coastal structures or by fill.
	Score =	100 90	89 60	59 30
15. Maintained channels, trawl areas, and SAV scars	<5% of bottom altered by dredging, trawling, prop damage, and harvesting.	5% to 14% of bottom altered by dredging, trawling, prop damage, and harvesting.	15% to 24% of bottom altered by dredging, trawling, prop damage, and harvesting.	\geq 25% of bottom altered by dredging, trawling, prop damage, and harvesting.
	Score =	100 90	89 60	59 30

¹ Marina is defined as an shoreline establishment that has 10 or more boat slips.

² NCDWQ threshold levels: chl a = 40 μ g/l, DO = 5 mg/l (NCDWQ 2008b).

³ Major exceedance event: chl a \geq 60 mg/l and/or more than 100 fish killed due to low DO and/or a report of a significant algal bloom; or >50% exceedance of toxicity threshold for toxicants.

⁴ Nutrient Sensitive Water: based on USEPA 303d impaired use for aquatic life classification

⁵ Turbidity threshold levels: 25 NTUs for streams and 50 NTUs for the receiving estuary

⁶ Tributary = First, second or third order streams that appear on USGS 1:24,000 hydrography maps.

⁷ Dam = mill dams and similar man-made structures.

⁸ Fourth or higher order streams: determined by USGS 1:24,000 hydrography maps.

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