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A study of anthropogenic and climatic disturbance of the New River Estuary using a Bayesian belief network

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ABSTRACT

The present paper utilizes a Bayesian Belief Network (BBN) approach to intuitively present and quantify our current understanding of the complex physical, chemical, and biological processes that lead to eutrophication in an estuarine ecosystem (New River Estuary, North Carolina, USA). The model is further used to explore the effects of plausible future climatic and nutrient pollution management scenarios on water quality indicators. The BBN, through visualizing the structure of the network, facilitates knowledge communication with managers/stakeholders who might not be experts in the underlying scientific disciplines. Moreover, the developed structure of the BBN is transferable to other comparable estuaries. The BBN nodes are discretized exploring a new approach called moment matching method. The conditional probability tables of the variables are driven by a large dataset (four years). Our results show interaction among various predictors and their impact on water quality indicators. The synergistic effects caution future management actions.

1. Introduction

Over the past two decades, more estuarine ecosystems across the globe have experienced eutrophication, defined as "an increase in the rate of supply of organic matter to an ecosystem" (Nixon, 1995; Rabalais et al., 2009). Estuaries are particularly susceptible to eutrophication due to riverine nutrient inflow, efficient nutrient trapping, long flushing times, and shallow depth. Moreover, climatic and anthropogenic perturbations have exacerbated eutrophication symptoms, through higher temperatures, extreme floods/droughts, and land use alterations, which further endangers estuarine ecological health (Neff et al., 2000; Cloern, 2001; Scavia et al., 2002; Lloret et al., 2008; Armstrong, 2009; Rabalais et al., 2009; Kaushal et al., 2010).

Our goals were to quantify the impact of eutrophication on the ecological health of estuaries, facilitate decision-making processes by managers, and develop tools for clear communication with stakeholders. To this end, we investigated potential drivers of eutrophication in an estuary using a Bayesian Belief Network (BBN) approach (Ryther and Dunstan, 1971; Strobl and Robillard, 2008; Conley et al., 2009; Sheldon and Alber, 2011).

BBNs are directed acyclic graphical models, composed of nodes and links, with embedded conditional probability tables associated with each node (Jensen and Nielsen, 2007; Heckerman, 2008). The BBNs' visual interface makes them a valuable tool to illustrate complicated connections and communicate scientific research with a wide range of stakeholders. Additionally, the BBNs' modularity makes them transferable to other estuaries, assuming the structure of the model is generalizable (Nixon, 1995; Smith, 2003) and accounting for ecosystem specific variability (Koller and Pfeffer, 1997; Jensen and Nielsen, 2007; Johnson et al., 2010). The developed model for the former estuary would act as prior information for the later estuary. The model can then be updated using data from the later estuary due to the Bayesian nature of the BBN (posterior $\propto$ likelihood of observed data $\times$ prior). Finally, BBNs accommodate our goal of scenario investigation (Uusitalo, 2007).

In this paper, we describe the study area, the dataset, and the BBN model construction and evaluation. Using the model, we explore potential impacts of climatic variability and management scenarios on the NRE's water quality.

2. Materials and methods

2.1. Study area

Our study area (see Fig. 1), the New River Estuary (NRE), located in Onslow County, North Carolina, USA, was a highly eutrophic estuary (1995–2002) with elevated levels of chlorophyll *a* (>60 μg/l), nitrogen (total dissolved nitrogen >1 mg/l), phosphorus

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(total dissolved phosphorus >0.1 mg/l), turbidity (secchi disk depth <1 m), occasional bottom water hypoxia (dissolved oxygen <2 mg/l), and nuisance/harmful algal blooms (Mallin et al., 2005). Even after the upgrade of the sewage treatment plant of the City of Jacksonville and the US Marine Corps Base at Camp Lejeune in 1998, moderate to severe eutrophication symptoms are still observed (NOAA, 1996; Mallin et al., 2005). Poor water quality has negatively impacted the regional commercial fisheries for blue crab and shrimp (NCDMF, 1993; Tomas et al., 2007). Although high nutrient concentrations and elevated chlorophyll *a* production extends along the 25 km of the NRE, eutrophication symptoms are most severe in Morgan Bay, our study area, near the head of the estuary (NOAA, 1996; Mallin et al., 2005).

The NRE Bayesian belief network was developed with water quality monitoring data from the Defense Coastal/Estuarine Research Program (DCERP), Aquatic Estuarine Monitoring component (RTI, 2013), unless otherwise stated. Eight stations along the length of the NRE were sampled on a monthly basis, starting in October 2007, for a range of physical, chemical, and biological variables. In this study, we used data from October 2007 to October 2012 for the three stations in the upper estuary (stations CL 6, CL7, and CL8 in the Morgan Bay) where eutrophication symptoms are most severe (Fig. 1) (Hall et al., 2012). Furthermore, the NRE is functionally divided into two shallow estuaries with different ecological properties, with the upper section showing stronger relations between chlorophyll *a* and nutrient concentrations (RTI, 2013). We used the data from October 2007 to September 2011 for model development and the remainder (i.e. October 2011–October 2012) for model validation purposes.

2.2. Model construction

We followed the guidelines on developing Bayesian belief network models suggested in the literature by undergoing several cycles of model development and revision (Marcot et al., 2006; Chen and Pollino, 2012). We implemented the BBN in the Hugin Educational 7.1 software package (Madsen et al., 2003).

The first step in developing the BBN was to determine the most important factors that were believed to have an impact on the eutrophication in the NRE. The number of variables and nodes of the BBN model depend on the purpose and scope of the study. Here our objective was to quantify the impacts of anthropogenic and climatic factors on water quality indicators (i.e. chlorophyll *a* concentrations, bottom water dissolved oxygen and presence/absence of harmful algal bloom species). To this end, we developed an ecological network with surface chlorophyll *a* concentrations, bottom water dissolved oxygen and presence/absence of harmful algae (toxic algae and/or hypoxia generating and/or food web disrupting) as key water quality indicators suggested by US EPA National Coastal Condition Report's suggestions (EPA, 2001a; EPA, 2001b; Sheldon and Alber, 2011) (Fig. 2). The variables within the BBN were compartmentalized into five functional components: "Physical Environment", "Chemical Environment", "Biological Environment", "Harmful Algae", and "Hypoxia/Anoxia" (Fig. 2), to accommodate our goal of investigating the impacts of anthropogenic nutrient pollution and climatic variability. One advantage of this compartmentalization is that the current components can be further expanded in the future or additional components such as land-use can later be developed and added as a sub-model to the current BBN.

We investigated a large selection of variables in the dataset (see supplementary material Table 2) using exploratory data analysis, personal communications with local experts and scientific literature during the variable selection procedure. We included the following variables in the model to predict surface chlorophyll *a* concentrations, bottom water dissolved oxygen and presence/absence of harmful algae (toxic algae and/or hypoxia generating and/or food web disrupting): wind speed (data from State Climate

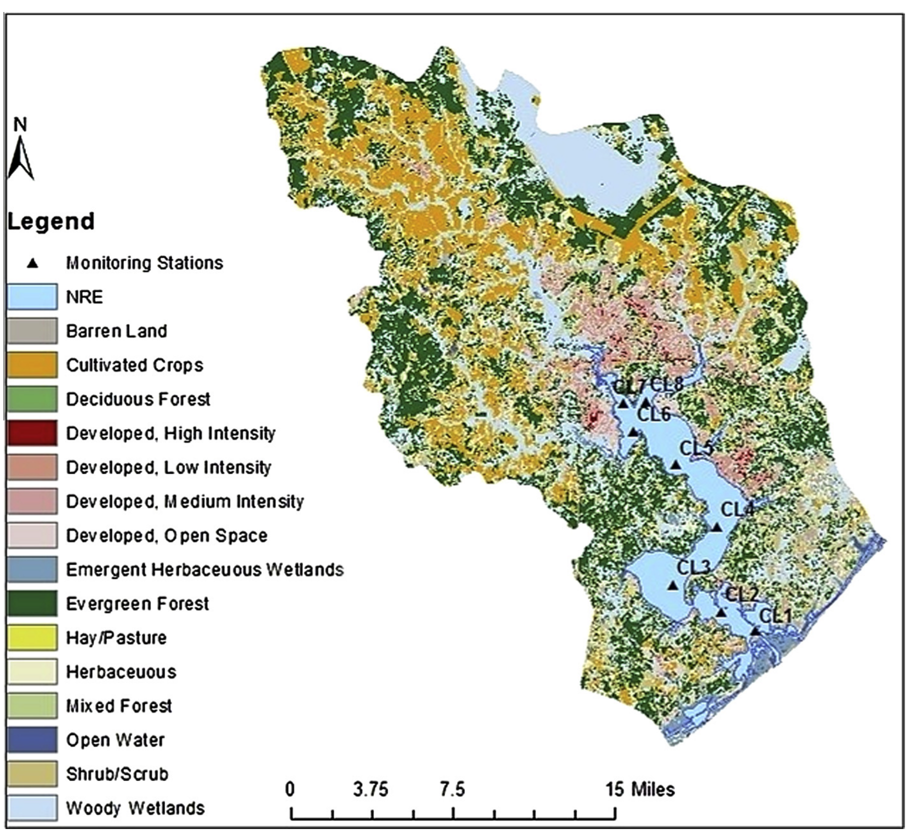

Fig. 1. New River Estuary, land use and cover, and monitoring stations. For the BBN, data from CL 6, CL7, and CL8 were used.

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