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A Bayesian changepoint–threshold model to examine the effect of TMDL implementation on the flow–nitrogen concentration relationship in the Neuse River basin

Ibrahim Alameddine, Song S. Qian, Kenneth H. Reckhow*

Nicholas School of the Environment, Duke University, Durham, NC 27708, USA

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ABSTRACT

In-stream nutrient concentrations are well known to exhibit a strong relationship with river flow. The use of flow measurements to predict nutrient concentrations and subsequently nutrient loads is common in water quality modeling. Nevertheless, most adopted models assume that the relationship between flow and concentration is fixed across time as well as across different flow regimes. In this study, we developed a Bayesian changepoint–threshold model that relaxes these constraints and allows for the identification and quantification of any changes in the underlying flow–concentration relationship across time. The results from our study support the occurrence of a changepoint in time around the year 1999, which coincided with the period of implementing nitrogen control measures as part of the TMDL program developed for the Neuse Estuary in North Carolina. The occurrence of the changepoint challenges the underlying assumption of temporal invariance in the flow–concentrations relationship. The model results also point towards a transition in the river nitrogen delivery system from a point source dominated loading system towards a more complicated nonlinear system, where non-point source nutrient delivery plays a major role. Moreover, we use the developed model to assess the effectiveness of the nitrogen reduction measures in achieving a 30% drop in loading. The results indicate that while there is a strong evidence of a load reduction, there still remains a high level of uncertainty associated with the mean nitrogen load reduction. We show that the level of uncertainty around the estimated load reduction is not random but is flow related.

1. Introduction

Anthropogenic nitrogen reaching rivers, lakes, estuaries, and coastal areas has been linked to eutrophication, acidification, adverse human health effects, the disruption of ecosystem functions, as well as the lowering of biodiversity in affected water bodies (Kelly, 2008 and references therein). High profile events such as the dramatic fish kills in the Neuse River and Estuary in mid 1980 and early 1990s as well as the development of extensive hypoxic zones in the Gulf of Mexico have been linked to excessive nitrogen release and delivery (Turner and Rabalais, 1994; Paerl et al., 1995; Paerl, 1997; Alexander et al., 2000, 2008; Scavia et al., 2003; Stow and Borsuk, 2003; Borsuk et al., 2004). Such events have stimulated an impetus towards the implementation of aggressive management and mitigation measures to limit the amount of nitrogen reaching the aquatic environment. While some successes have been made in some water bodies, water

* *Corresponding author*. Tel.: +1 919 613 8054; fax: +1 919 681 5740.
E-mail address: ima4@duke.edu (I. Alameddine).

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Nomenclature

log	natural logarithm
N	normal distribution
Unif	uniform distribution
Q	daily mean flow (m^3/s)
$\sim$	distributed
$\widehat{X}$	the mean of parameter X
α	the model intercept
$\beta_{j,k}$	slope on the river flow (in natural log scale)
β_{Temp}	slope on water temperature measured in °C
σ	standard deviation
δ	a variable that is added to the slope on river flow to account for the occurrence of a flow threshold
i	index of observation
j	logical operator that returns a value of 1 for pre changepoint observations and a value of 2 for post changepoint observations, where a changepoint is an instance in time when the system changes its behavior
k	logical operator that returns a value of 1 for flow values below the flood threshold and a value of 2 for flow values above the flood threshold
n	number of observations
θ	set of model parameters
Min	returns the minimum value from a vector of values
Max	returns the maximum value from a vector of values
ε	error term (assumed to be Gaussian white noise)

quality impairment from excessive nitrogen loading continues to be a pressing issue on the national as well as international levels. Currently nutrient impairment ranks fourth on the national impairment list with 6826 water bodies listed as impaired due to excessive nutrient loading (out of a total of 75,677 impairment causes). Of these around 17% have nitrogen explicitly listed as the cause of impairment (Environmental Protection Agency, 2009).

The Neuse River and its associated estuary in North Carolina have experienced all the symptoms of eutrophication with extensive algal blooms, fish kills, hypoxia and anoxia that have captured the public attention in the 1980s and 1990s (Paerl et al., 1998). This led to designating the Neuse as a nutrient sensitive water and prompted its listing on the 303 (d) list with nitrogen identified as the main culprit behind eutrophication (Paerl et al., 1995; Stow et al., 2003). In 1998, the USEPA settled a lawsuit brought by the Neuse River Foundation which required North Carolina to establish a Total Maximum Daily Load (TMDL) for nitrogen reaching the estuary. The TMDL was approved by USEPA on August 26, 1999. Meanwhile, the State of North Carolina, through the North Carolina Division of Water Quality (NCDWQ), adopted in 1997 a set of rules that aimed at reducing the amount of nitrogen delivered to the Neuse River Estuary by 30% based on 1991–1995 loads. Despite almost a decade of post-TMDL monitoring, there has been no consensus on whether the TMDL has achieved its stated goal and if the implemented management measures have been successful (Deamer, 2009).

To better understand the nitrogen dynamics and the effectiveness of the TMDL program in the Neuse over time, we made use of daily flow measurements to estimate nitrogen concentrations and nitrogen loading rates in the Neuse. The use of flow measurements to predict nutrient concentrations (and thus load) is common in water quality modeling given that in-stream nutrient concentrations have been observed to exhibit a relationship with river/stream flow (Johnson, 1979; Reckhow and Stow, 1990; Stow and Borsuk, 2003). The development of flow–concentration (as well as flow-load) models are often used to draw upon the large databases of daily flow measurements in order to augment infrequent water quality sampling measurements.

The use of regression-based empirical methods to predict daily nutrient loading through the use of daily averaged river flow measurements is one of the more commonly used approaches to determine nutrient concentrations/loads (Cohn et al., 1992; Green and Haggard, 2001; Hooper et al., 2001; Haggard et al., 2003; Runkel et al., 2004; Ide et al., 2007). This approach is based primarily on the work of Cohn et al. (1992) who developed the “rating curve” method that involves a log-linear multivariate regression model linking flow to concentration and load. While refinements have been added to the original “rating curve” method, most of the adopted models assume that the relationship between flow and concentration is fixed over time as well as across the range of river flows.

The implementation of environmental management measures at a river basin scale can often result in changes to the underlying relationship linking flow to concentration measurements, and ultimately affect load estimates. With the implementation of basin-scale water quality management plans in different river systems, it is becoming increasingly imperative to evaluate the effects that such basin-scale management plans (like the TMDL program) has on these systems. So far, however, there has been little chance to conduct such as assessment due to the difficulty of finding a river system with both a long monitoring record and that has had TMDL mitigation measures put in place. The Neuse River presents a unique opportunity to study these changes and demonstrate their impacts due to the presence of a monitoring program that stretched for over 30 years, during which a TMDL program has been enforced.

The objective of this paper is to assess the dynamics of the relationship of nitrogen concentration and flow between 1979 and 2008 in order to determine whether the relationship has been time invariant or if it has experienced a major changepoint across time. The occurrence of a system changepoint at a specific point in time often signifies an abrupt change in the way a system operates or behaves. These system changes may involve changes to the model parameters, the underlying model structure, or changes to both. We use Total Oxidized Nitrogen (TON) (which is the sum of nitrate (NO_3^-) and nitrite (NO_2^-)) concentrations in the Neuse, given its long historical