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Decadal and seasonal trends of nutrient concentration and export from highly managed coastal catchments

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ABSTRACT

Understanding anthropogenic and hydro-climatic influences on nutrient concentrations and export from highly managed catchments often necessitates trend detection using long-term monitoring data. This study analyzed the temporal trend (1979–2014) of total nitrogen (TN) and total phosphorus (TP) concentrations and export from four adjacent coastal basins in south Florida where land and water resources are highly managed through an intricate canal network. The method of integrated seasonal-trend decomposition using LOESS (LOcally weighted regrESSion) was employed for trend detection. The results indicated that long-term trends in TN and TP concentrations (increasing/decreasing) varied with basins and nutrient species, reflecting the influence of basin specific land and water management practices. These long-term trends were intervened by short-term highs driven by high rainfall and discharges and lows associated with regional droughts. Seasonal variations in TP were more apparent than for TN. Nutrient export exhibited a chemostatic behavior for TN from all the basins, largely due to the biogenic nature of organic N associated with the ubiquity of organic materials in the managed canal network. Varying degrees of chemodynamic export was present for TP, reflecting complex biogeochemical responses to the legacy of long-term fertilization, low soil P holding capacity, and intensive stormwater management. The anthropogenic and hydro-climatic influences on nutrient concentration and export behavior had great implications in nutrient loading abatement strategies for aquatic ecosystem restoration of the downstream receiving waterbody.

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1. Introduction

Elevated nutrient concentrations and export from intensively managed catchments are increasingly linked to water quality problems and ecological degradation of downstream receiving water bodies at both regional and global scales (Seitzinger et al., 2005; Diaz and Rosenberg, 2008; Rabalais et al., 2010). The temporal and spatial variability in nutrient concentrations and export stems from natural processes including rainfall and climatic conditions and human impacts from agriculture and urban discharges. Understanding these anthropogenic and hydro-climatic influences on aquatic environment and ecological processes often necessitates trend detection and evaluation of water quality and nutrient export based on long-term monitoring data (Wilcock et al., 2013; Akyuz et al., 2014; Ballantine and Davies-Colley, 2014; Liang et al., 2014; Wu and Xia, 2014).

The interplay between concentration C (water quality) and discharge Q (hydrology) has been a subject of research for decades (e.g., Johnson, 1979; Hirsch et al., 2010). Analyses of C-Q relationships can be used to characterize nutrient export from catchments in terms of chemostatic (C does not change with Q) and chemodynamic (C changes with Q) (Thompson et al., 2011; Musolff et al., 2015). Recently, an analogy has been made between exports of geogenic solutes (weathering products) from nearly natural catchments (Godsey et al., 2009) and nutrients (N and P) from highly managed agricultural catchments (Basu et al., 2010; Thompson et al., 2011), whereby concentrations were found relatively stable with time in spite of large variations in discharges for both cases. While land use change and the associated fertilization practices were often the causes for increasing or decreasing trend of

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nutrient concentrations in managed catchments (e.g., Green et al., 2014), possible reasons for an observed chemostatic behavior were linked to saturation of nutrients in catchments where a long history of intensive agricultural use resulted in a transport limited rather than supply limited regime (Basu et al., 2010; Thompson et al., 2011). Thus, the export behavior may reflect the biogeochemical nature of a particular nutrient in relation to site specific conditions of the catchment.

A few studies have proposed metrics to quantify the export behaviors. Using a power law relationship between concentration C and discharge Q: $C = aQ^b$, Godsey et al. (2009) defined the chemostatic response as $b \approx 0$. Basu et al. (2010) used the coefficient of determination (r^2) of linear regression between annual load (L) and annual discharge (Q) as a measure of chemostatic behavior, which implied linearity in the L to Q relationship. They further noted that L-Q $r^2 > 0.8$ provides a valid indication of effective geochemical stationarity at the annual timescale. Note that L-Q $r^2 > 0.8$ is used to infer invariant concentrations with changing discharges. The metrics of Godsey et al. (2009) and Basu et al. (2010) are not always consistent with each other as Basu et al. (2010) noted that $r^2 > 0.8$ can be observed for $-0.4 < b < 1.4$ in $C = aQ^b$. To reconcile the inconsistency, Thompson et al. (2011) proposed the ratio of coefficient of variation (CV) of concentration and discharge (CV_C/CV_Q) as a metric. Thus, chemostatic behavior could be considered a case where the variability in concentration was highly buffered compared to that of discharge, i.e., $CV_C/CV_Q \ll 1$. In other words, the variation in exported load is driven primarily by the variation in flow, not by variation in concentration. Thompson et al. (2011) further noted that $CV_C/CV_Q < 0.3$ represents the chemostatic behavior.

In regardless of the difference in metrics, the period of records of available data (time) is a key factor that is implicitly embedded in the calculation. Most workers studied solute export behaviors with no attentions being paid to examine whether the C-Q or L-Q relationships would change with time in a catchment (Godsey et al., 2009; Basu et al., 2010; Thompson et al., 2011). Water quality generally changes over long periods of record (decades) in response to management actions in watersheds (James et al., 2011; Wilcock et al., 2013; Green et al., 2014). South Florida is a unique system featuring a subtropical climate with distinct wet and dry seasons and a flat landscape where rapid agricultural and urban development has occurred over the past decades with construction of an intricate canal network. The site specific nature of land and water management and nutrient export warrants an examination of catchments in south Florida where nonpoint source pollution control has become a key component of large scale ecosystem restoration efforts (Chimney and Goforth, 2001).

Another important line of research is on the techniques used for water quality trend detection. A review of recent literature (Table S1) revealed that most environmental trend analyses involved unidirectional linear or quadratic regressions (parametric) or Mann-Kendall/seasonal Kendall tests (non-parametric) to discern long-term water quality trends in responses to basin management activities or reduced nutrient loading from point and nonpoint sources (e.g., Williams et al., 2010; Chiueh et al., 2011; Stewart et al., 2011; Kauffman et al., 2011; Elci and Selcuk, 2013; David et al., 2013). While these statistical tools are useful, they are constrained to linear or monotonic trend detection and fail to reveal trend reversals during the evaluation period (Qian et al., 2000). Water quality changes often exhibit short-term departures from a long-term trend in response to human disturbance and natural drivers.

To address the linearity issue in trend detection, techniques stemming from the general additive models for seasonal time series decomposition using locally weighted regression (LOESS) have been developed (Cleveland, 1979; Cleveland et al., 1990; Hirsch et al., 2010). For example, the seasonal trend decomposition using LOESS (STL), an iterative, nonparametric, graphical method was introduced in 1990 for describing nonlinear trends with seasonal interaction (Cleveland et al., 1990). The non-parametric and graphic nature of STL makes it flexible in revealing changes in timing, amplitude, and variance that occur over seasonal cycles (Qian et al., 2000), occupying a much wider range of component patterns than single parametric methods (Hafen et al., 2009). Since its initial application by Cleveland et al. (1990) in analyzing atmospheric CO_2 concentration, several workers have used the method in water quality studies with Qian et al. (2000) examining spatiotemporal variations in nutrient concentrations in the Neuse River and Estuary, North Carolina (USA), Liang et al. (2014) identifying water quality trends in Lake Dianchi, China, and Stow et al. (2015) determining long-term trends and seasonal patterns in Maumee River discharge, rainfall, nutrient concentrations, and loads. Rooted in the same concept, the WRTDS (Weighted Regressions on Time, Discharge, and Season) model was recently introduced by Hirsch et al. (2010) and applied in several studies (e.g., Green et al., 2014), offering comparable functionalities to STL. The WRTDS model has additional robust features for detecting flow-normalized trends and exploring explicit trends in response to changes in flow.

In this study, we applied the STL methodology to examine the effect of land use changes and hydro-climatic drivers on temporal trends in rainfall, flow, stormwater nutrient concentrations and export from four highly managed catchments discharging into the St. Lucie Estuary (SLE) and Indian River Lagoon (IRL), Florida, U.S.A. The IRL/SLE system has received considerable attention due to concerns of excessive nutrient loading from the watershed (Doering, 1996; Wan et al., 2012). Over the past 40 years, the watershed has experienced large scale land use change along with multiple hurricanes that generated record rainfall and several droughts affecting water supply in the region. Specifically, the objectives of this study were to (i) identify both long-term (decadal) and short-term (seasonal) trends in nutrient concentrations using the STL method with special emphasis on the past 15 years when major land use change and hydrological events occurred in the region; and (ii) explore land and water management and hydro-climatic controls on nutrient concentrations in relation to chemostatic/chemodynamic nutrient export behaviors. To aid in the analysis, land use coverage and hydrometric data (discharge and rainfall) were integrated into 35 years of water quality data collected at outlets of the four adjacent drainage basins discharging into the IRL/SLE system.

2. Methods

2.1. Study area

The Indian River Lagoon, located on the southeast coast of Florida (Fig. 1), is regarded as one of the most biologically diverse ecosystems in North America with approximately 2200 identified plant and animal species (Swain et al., 1995). The St. Lucie Estuary is the largest tributary to the IRL. Prior to development, the IRL/SLE watershed was characterized by nearly level terrain and poorly drained upland forest and wet prairie (Wan et al., 2006). Over the last century, land use and drainage patterns have undergone substantial changes after construction of a network of primary, secondary, and tertiary canals (Fig. 1), draining a total area of 2694 km^2. The large primary canals managed by the South Florida Water Management District (SFWMD) and the U.S. Army Corps of Engineers (USACE) include C44 (completed in 1924 and enlarged to its current size in 1949), C23, C24, and C25 (completed *circa* 1961). These were constructed to allow for widespread agricultural and