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A modification of the Regional Nutrient Management model (ReNuMa) to identify long-term changes in riverine nitrogen sources

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ABSTRACT

Source apportionment is critical for guiding development of efficient watershed nitrogen (N) pollution control measures. The ReNuMa (Regional Nutrient Management) model, a semi-empirical, semi-process-oriented model with modest data requirements, has been widely used for riverine N source apportionment. However, the ReNuMa model contains limitations for addressing long-term N dynamics by ignoring temporal changes in atmospheric N deposition rates and N-leaching lag effects. This work modified the ReNuMa model by revising the source code to allow yearly changes in atmospheric N deposition and incorporation of N-leaching lag effects into N transport processes. The appropriate N-leaching lag time was determined from cross-correlation analysis between annual watershed individual N source inputs and riverine N export. Accuracy of the modified ReNuMa model was demonstrated through analysis of a 31-year water quality record (1980–2010) from the Yongan watershed in eastern China. The revisions considerably improved the accuracy (Nash-Sutcliff coefficient increased by ~0.2) of the modified ReNuMa model for predicting riverine N loads. The modified model explicitly identified annual and seasonal changes in contributions of various N sources (i.e., point vs. nonpoint source, surface runoff vs. groundwater) to riverine N loads as well as the fate of watershed anthropogenic N inputs. Model results were consistent with previously modeled or observed lag time length as well as changes in riverine chloride and nitrate concentrations during the low-flow regime and available N levels in agricultural soils of this watershed. The modified ReNuMa model is applicable for addressing long-term changes in riverine N sources, providing decision-makers with critical information for guiding watershed N pollution control strategies.

1. Introduction

Increasing anthropogenic nitrogen (N) inputs have substantially elevated riverine N loads worldwide, resulting in degradation of aquatic ecosystem health, impaired water quality for some beneficial uses, and eutrophication and hypoxia in many coastal ecosystems (Galloway et al., 2008; Howarth et al., 2012). To control N pollution effectively, quantitative assessment and identification of riverine N sources are required for optimizing pollution control strategies at the watershed scale.

Many lumped (e.g., export coefficient models, SPARROW, and PolFlow) and mechanistic models (e.g., AGNPS, HSPF, and SWAT) (De Wit et al., 2000; Moriasiet al., 2007; Li et al., 2015; Du et al., 2014) are available for quantifying riverine N sources. Although potentially more accurate results are obtainable from mechanistic watershed models, a major limitation is their requirement for a large amount of input data for calibration/validation of a given watershed making their application difficult and labor intensive for the large number of watersheds requiring assessment (Shrestha et al., 2008; Shen and Zhao, 2010; Chen et al., 2013). In contrast, export coefficient and statistical models require fewer data inputs but are limited by their annual time step, which makes it difficult to infer seasonal patterns of nutrient delivery (Chen et al., 2013). Such seasonal resolution is required to determine nutrient sources and loads during the most sensitive times of the year (e.g., typically the summer growing season) when eutrophication/hypoxia is most likely to occur in downstream water bodies (May et al., 2001; Bowes et al., 2009). The ReNuMa (Regional Nutrient Management) model, a semi-empirical and semi-process-oriented watershed model with modest and easily acquired data requirements (e.g., precipitation, temperature, land-use data, point source load, fertilizer and manure loads), provides an attractive alternative for addressing seasonal nutrient dynamics with acceptable accuracy (Hong and Swaney, 2013).

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Due to its attributes, the ReNuMa model has been widely applied for simulating temporal variations of river discharge and riverine nutrient sources in a range of watersheds with contrasting climate, geology and land use (Brandmeyer et al., 2007; Woodbury et al., 2008; Liu et al., 2012; Xie, 2012; Sha et al., 2013, 2014; Huang, 2014; Li et al., 2014; Lu et al., 2014). These previous studies using ReNuMa were successfully validated for N dynamics at relatively short-time scales ($<$ 10 years). In contrast, long-term studies are necessary for exploring drivers and trends in riverine N pollution (Chen et al., 2014), since management decisions made on short-term data sets (even up to 15 years) could be misleading (Burt et al., 2008) and temporal fluctuations caused by climatic variation may be misinterpreted as resulting from human activities (Howden et al., 2011). With respect to the ReNuMa model, challenges exist in addressing long-term watershed N dynamics (Sha et al., 2013) related to the steady-state assumptions for atmospheric N deposition and transient storage of N in soils and aquifers.

Over longer time periods (several decades), atmospheric N deposition in a given watershed or region may experience large changes due to changing human activities. For example, a steady decline (~41% decline) in atmospheric N deposition from 1990 to 2010 was observed in many American regions due to effective controls on NO_x emissions (Davidson et al., 2011; Ellis et al., 2013). In contrast, a dramatic increase of N deposition (~60% increase) occurred in many regions in China (especially southeastern China, ~170% increase) from 1980 to 2010 due to rapid increases in consumption of fossil fuels and fertilizers (Liu et al., 2013). Previous studies of watershed N dynamics also indicate long transit times for N passing through soils, vadose zone and groundwater to surface waters (Meals et al., 2010; Sanford and Pope, 2013; Sebilo et al., 2013; Bouraoui and Grizzetti, 2014; Van Meter et al., 2017; Chen et al., 2018). This N transport lag time (i.e., time elapsed between watershed N inputs and riverine N export) can range from several years to decades (Meals et al., 2010; Hamilton, 2012; Chen et al., 2015b), implying that a considerable proportion of the current riverine N load may be derived from legacy N inputs (Chen et al., 2018; Van Meter et al., 2017). Therefore, the assumption of steady-state atmospheric N deposition inputs and transient storage of N in soils and aquifers in the ReNuMa model could introduce considerable uncertainty in addressing long-term changes in riverine N sources.

This study is the first attempt to address long-term (three decades) watershed-scale N dynamics using a version of the ReNuMa model that was modified to consider yearly changes in atmospheric N input and N-leaching lag effects with minimal additional data requirements. The model source code was revised to incorporate monthly changes in atmospheric N deposition rates over the entire study period. A cross-correlation analysis was adopted to determine the appropriate length of the multi-year period that should be used to estimate average nonpoint source N inputs to satisfy the steady-state assumption for predicting riverine N export. The accuracy of the modified model was assessed through analysis of a 31-year record (1980–2010) of riverine total N (TN) loads from the Yongan River watershed in eastern China, an area experiencing rapid economic development over the study period. The modified model retains the merits but overcomes selected limitations of the original ReNuMa model, providing decision-makers with a tool for informed management and mitigation of N pollution at the watershed scale.

2. Materials and methods

2.1. Study area

The Yongan River watershed is a representative mesoscale watershed (2474 km^2) in southeastern China that has experienced dramatic changes in N deposition and anthropogenic activities in the past three decades. The Yongan River is the third largest river of Zhejiang province and flows to the East China Sea (Fig. 1). The East China Sea coastal zone, downstream of the Yongan watershed, is a frequent region for eutrophication during May to October (Chen et al., 2007). The climate is subtropical monsoon having an average annual temperature of 17.4 °C and average annual precipitation of 1400 mm (Fig. 2a). The rainfall mainly occurs in May–October with a typhoon season occurring in July–September. The May–October period is considered the primary growing season, which is the most active period for agricultural activities. Total population within the watershed increased from ~590,000 to ~740,000 between 1980 and 2010. Over the 31-year study period, domestic livestock production (pig, cow, sheep and rabbit) decreased by ~25%, while poultry production (chicken and duck) increased 4.8-fold (Chen et al., 2015b). Agricultural land (including paddy field, garden plot and dry land, Table S1) averaged ~12% of total watershed area in 1980–2010 (Fig. 2b), with developed lands, forest, and barren land (including surface waters, wetlands, rock, and wildlands) contributing ~3, ~67, and ~18%, respectively. The economic role of agriculture has been increasingly replaced by industry since the 1990s, resulting in a remarkable reduction (~40%) in chemical N fertilizer application since 2000 (Fig. 2c). The agricultural land area irrigated and drained with cement channels and pipes increased by ~2-fold since 2000 (Supplementary materials, Part A, 1).

2.2. Data preparation

Data inputs for the ReNuMa model include a series of parameter values and watershed monitoring data. Annual and seasonal riverine TN loads were estimated by LOADEST based on discrete TN concentration and daily river water discharge monitoring data (Supplementary materials, Part A, 2). Daily average temperature and precipitation were averaged from three monitoring stations located within the watershed (Fig. 1). Due to the high seasonal dependence of water discharge (Fig. 2a) and nutrient inputs, this study split the year into growing (May–October) and dormant (November–April) seasons. Land use (Fig. 2b) and population data for the 1980–2010 period were derived from local government yearbooks of Xianju County and Linhai City. Monthly nitrogen input data from various sources were processed to meet the model requirements (Table 1). Atmospheric deposition was obtained from annual average N deposition records reported for southeast China in 1980–2010 (Liu et al., 2013) and N emissions from crop residue burning were subtracted. These net atmospheric N deposition values were multiplied by a precipitation normalization index to obtain the slope and intercept for N deposition. Annual chemical and organic fertilizer N inputs were estimated by the applied amount of each fertilizer type and corresponding N content, and further divided by the area of agricultural land-use types to acquire the fertilizer application rate (kg-N ha^{-1} agricultural area yr^{-1}). Fertilizer application was assumed to occur in March as only the annual totals affect the dissolved N concentrations in the current model formulation. Manure application was processed in the same manner as fertilizer application. Monthly agricultural biological N fixation was based on data from a nearby region, which specified different N fixation percentages for different months (Li et al., 2014). Point source nutrient loads were estimated as the sum of domestic and industrial sources, and divided by 12 to obtain monthly point-source N loads (Table 1; Supplementary materials, Part A, 3).

2.3. The ReNuMa model framework and modifications

The ReNuMa model, a hydrologically-driven, quasi-empirical model is designed to estimate nutrient loads in mesoscale watersheds (up to several thousand km^2). It is based on a large-catchment transport model (Generalized Watershed Loading Function model; Haith et al., 1996) and a nitrogen-budgeting approach that sums N contributions from net food and feed transport across watershed boundaries, atmospheric N deposition, fertilizer application (including manure), and nitrogen fixation within the watershed (Hong and Swaney, 2013). Output from the ReNuMa model summarizes N inputs from different sources (e.g.,