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Research article

Nitrogen Source Inventory and Loading Tool: An integrated approach toward restoration of water-quality impaired karst springs

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ABSTRACT

Nitrogen (N) from anthropogenic sources has contaminated groundwater used as drinking water in addition to impairing water quality and ecosystem health of karst springs. The Nitrogen Source Inventory and Loading Tool (NSILT) was developed as an ArcGIS and spreadsheet-based approach that provides spatial estimates of current nitrogen (N) inputs to the land surface and loads to groundwater from nonpoint and point sources within the groundwater contributing area. The NSILT involves a three-step approach where local and regional land use practices and N sources are evaluated to: (1) estimate N input to the land surface, (2) quantify subsurface environmental attenuation, and (3) assess regional recharge to the aquifer. NSILT was used to assess nitrogen loading to groundwater in two karst spring areas in west-central Florida: Rainbow Springs (RS) and Kings Bay (KB). The karstic Upper Floridan aquifer (UFA) is the source of water discharging to the springs in both areas. In the KB study area (predominantly urban land use), septic systems and urban fertilizers contribute 48% and 22%, respectively, of the estimated total annual N load to groundwater 294,400 kg-N/yr. In contrast for the RS study area (predominantly agricultural land use), livestock operations and crop fertilizers contribute 50% and 13%, respectively, of the estimated N load to groundwater. Using overall groundwater N loading rates for the KB and RS study areas, 4.4 and 3.3 kg N/ha, respectively, and spatial recharge rates, the calculated groundwater nitrate-N concentration (2.1 mg/L) agreed closely with the median nitrate-N concentration (1.7 mg/L) from groundwater samples in agricultural land use areas in the RS study area for the period 2010–2014. NSILT results provide critical information for prioritizing and designing restoration efforts for water-quality impaired springs and spring runs affected by multiple sources of nitrogen loading to groundwater. The calculated groundwater N concentration for the KB study area (1.45 mg/L) was approximately three times higher than the median N concentration (0.45 mg/L) for wells located in urban land use areas.

1. Introduction

Nitrate-N (NO_3-N), the most persistent and mobile form of nitrogen in the subsurface has caused degradation of karst aquifers and their associated spring systems in many places around the world (Nolan and Stone, 2000; Kingsbury, 2008; Obeidat et al., 2008; Siliang et al., 2010). Nitrogen (N) that is deposited on or applied to the land surface from a variety of nonpoint and point sources can convert readily to NO_3; subsequently, moving relatively rapidly and unimpeded through sinkholes and other dissolution features directly into karst aquifer systems. NO_3-N-contaminated groundwater discharging to karst springs and spring runs has resulted in degraded ecosystems, which has created a shift in the ecological balance from healthy native aquatic vegetation to extensive algal mats and invasive plants (Cohen et al., 2007; Mattson et al., 2007). In addition, NO_3-N and nitrite (NO_2) may affect the metabolic processes in fishes and reptiles through disruption of hormone synthesis (Guillette and Edwards, 2005). Human health issues associated with nitrate in drinking water include methemoglobinemia (Johnson et al., 1987), and several types of cancer (Ward et al., 2005; DeRoos et al., 2003).

Groundwater recharge areas can contain a mixture of agricultural and urban land uses, both contributing N from multiple sources such as fertilizers (applied on cropland, and turfgrass used for lawns and, recreational activities), livestock wastes, the land application of treated municipal wastewater, on-site treatment and

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disposal systems (septic systems), and atmospheric deposition. Several approaches have been used to assess the dominant sources of nitrate contamination in karst spring basins. Isotopes of NO_3-N and/or other chemical tracers have been used to distinguish between inorganic and organic N sources (Panno et al., 2001; Katz, 2004; Albertin et al., 2012), but typically do not provide critical quantitative information on the relative contribution from multiple sources of inorganic and organic N. To obtain detailed source loading estimates, several studies have used a combination of land use information along with associated N source information on application rates to estimate N inputs to the land surface (Chelette et al., 2002; Jones et al., 1996, 1998; Panno et al., 2008; Katz et al., 2009). Some of these studies have accounted for N attenuation rates in the subsurface and subsequent leaching to groundwater; however, these studies typically have not accounted for spatial variations in recharge rates to groundwater in contributing areas.

Identifying and quantifying the relative contributions of N from multiple sources in groundwater contributing areas of large karst spring systems are fundamental for developing effective and efficient restoration strategies. Water-quality degradation of springs from nutrient enrichment of groundwater has become a serious environmental concern in Florida and elsewhere (Nolan and Stone, 2000; Kingsbury, 2008; Obeidat et al., 2008; Siliang et al., 2010). In response to these concerns, the Nitrogen Source Inventory and Loading Tool (NSILT) was developed to identify and quantify current inputs of N to the land surface and associated N loads to groundwater from major sources in spring basins or other designated areas. NSILT methodology provides more robust N loading estimates to groundwater in comparison to previous studies because it incorporates detailed land use information from property appraisers, data from surveys on fertilizer usage and livestock waste management practices, spatial information on aquifer recharge rates, and N attenuation processes in the subsurface.

This paper describes the NSILT approach and how this tool was used to evaluate the relative contributions of nitrogen from various sources in two karst spring systems in Florida: one dominated by agricultural land use, the other by urban land use. This information is critical for prioritizing and designing strategies for restoring water-quality in impaired spring systems affected by elevated groundwater nitrogen concentrations.

2. NSILT approach and methodology

NSILT is an ArcGIS- and spreadsheet-based methodology that incorporates comprehensive and current information on recharge, land use, and anthropogenic N sources. The various components included in NSILT are shown in Fig. 1. The following sections describe the methods used to quantify the current N source inputs to the land surface within a designated groundwater contributing area (from atmospheric deposition, septic systems, wastewater treatment facilities, urban fertilizers, agricultural fertilizers and livestock waste). N loads to groundwater are estimated by taking into account N losses from biochemical and hydrogeological processes (discussed further in section 3.3) that attenuate N as it moves from the land surface to the groundwater system. (Equation (1)).

$$N_{gw}\left(\frac{kg}{yr}\right) = \sum (N_{input} - N_{loss}) \quad (1)$$

N_{gw} = load (kg) of nitrogen to groundwater per year.
N_{input} = input of nitrogen (kg) to land surface per year.
N_{loss} = loss of nitrogen to the utilization and attenuation of nitrogen on the land surface and in the subsurface.

NSILT approach does not account for legacy loads of nitrogen that have entered the groundwater system over the past several decades and continue to adversely impact groundwater water quality in some areas. Previous studies have reported increasing nitrate-N concentrations in groundwater and springs over time. Nitrogen that entered groundwater from past anthropogenic practices may slowly exit the groundwater system given that the average groundwater residence times in large spring systems can be on the order of decades (Katz et al., 1999; Katz, 2004; Phelps, 2004; Happell et al., 2006; Knowles et al., 2010).

2.1. Nitrogen inputs to the land surface

2.1.1. Atmospheric deposition

N inputs to the land surface from atmospheric deposition (wet and dry) are estimated using data from the total deposition (TDEP) model developed by EPA for N deposition across the entire United States (Schwede and Lear, 2014). TDEP uses a hybrid approach for estimating total atmospheric deposition and incorporates nitrogen data from discreet monitoring stations, atmospheric concentrations and other air quality models. Data for wet, dry and total deposition are summarized in TDEP for 16 km^2 grid cells and available for a range of model years.

2.1.2. Wastewater treatment facilities

Wastewater Treatment Facilities (WWTFs) are permitted

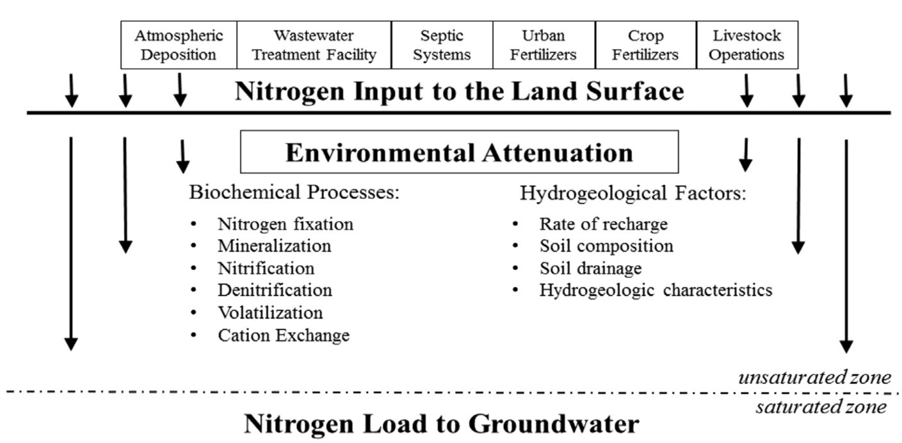

Fig. 1. NSILT components include N source inputs to the land surface, N attenuation processes in the unsaturated zone, and N loading to groundwater.