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Net anthropogenic nitrogen inputs and nitrogen fluxes from Indian watersheds: An initial assessment

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ABSTRACT

In this paper, we apply an established methodology for estimating Net Anthropogenic Nitrogen Inputs (NANI) to India and its major watersheds. Our primary goal here is to provide initial estimates of major nitrogen inputs of NANI for India, at the country level and for major Indian watersheds, including data sources and parameter estimates, making some assumptions as needed in areas of limited data availability. Despite data limitations, we believe that it is clear that the main anthropogenic N source is agricultural fertilizer, which is being produced and applied at a growing rate, followed by N fixation associated with rice, leguminous crops, and sugar cane. While India appears to be a net exporter of N in food/feed as reported elsewhere (Lassaletta et al., 2013b), the balance of N associated with exports and imports of protein in food and feedstuffs is sensitive to protein content and somewhat uncertain. While correlating watershed N inputs with riverine N fluxes is problematic due in part to limited available riverine data, we have assembled some data for comparative purposes. We also suggest possible improvements in methods for future studies, and the potential for estimating riverine N fluxes to coastal waters.
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1. Introduction

Anthropogenic nitrogen loads are the sources of many coastal water quality problems globally (UNEP, 2007), including rivers and bays in the United States (Bricker et al., 2007), Europe (Billen et al., 2011) and Asia (UNEP, 2007). Nitrogen enrichment of fresh and coastal waters has been linked to both ecological and human health issues, including impaired drinking water quality, harmful algal blooms, acidification, eutrophication, hypoxia, reduced fishery production, global climate change and loss of biodiversity (Howarth et al., 2012; NRC, 2000; Townsend et al., 2003, 2009). To address such problems, tools for quantification of nitrogen fluxes, sources and sinks, and their relationships to anthropogenic activities and landscape processes, hydrology and climate, are essential, the most basic of which is a nutrient budget. A range of models exists from field to global scales (Alexander et al., 2002; Leip et al., 2011; Mayorga et al., 2010; NRC, 2000) to assess N fluxes, most of which provide basic budget calculations because some level of "nutrient accounting" is useful to understand the dominant contributors to N loading in any region. It is also the case that N mass balances (budgets) can be constructed for a region without using an elaborate N model, simply on the basis of observational data or a combination of model results and observations, assuming that they are sufficient to provide estimates of major inputs and outputs for the system of interest.

NANI (Net Anthropogenic Nitrogen Inputs), first introduced by Howarth et al., (1996), provides an estimate of the nitrogen inputs associated with human activities to a watershed or region, or entire nation. The approach has been refined and applied to many regions since its introduction (Boyer et al., 2002; Han and Allan, 2008; Han et al., 2009; Hong et al., 2012, 2013; Howarth et al., 1996, 2006, 2012; Lassaletta et al., 2012, 2013a; Schaefer and Alber, 2007; Sprague and Gronberg, 2012). In developed regions of the world, the N cycle is usually dominated by these anthropogenic terms, so NANI is a good indication of the overall level of N load to a watershed. NANI is typically calculated as the sum of four major components: oxidized N deposition, fertilizer N application, agricultural N fixation, and N in net food and feed imports (NFF). The NFFs in turn are estimated as the difference between N in agricultural production (crops and livestock), which removes N from watersheds and into crop and livestock products, and consumption by humans and livestock, which ultimately adds to watershed N loads through manure and human waste. (In some regions, non-food crops, such as cotton and other fiber crops, are also included in this term. While they are not consumed as food, their production also adds to the regional crop demand for N, as is the case here). NANI estimates human-generated nitrogen inputs to a watershed and has been shown to be a good predictor of riverine nitrogen export, which typically ranges from 20% to 30% of NANI in temperate regions, e.g. across watersheds of the US, Europe and Asia on scales averaging thousands of km^2, over five years or more (Howarth et al., 2012; Swaney et al., 2012). In arid regions, the proportion of riverine export can be much lower

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(8%–12%), due to higher retention associated with lower flows (Howarth et al., 2012; Lassaletta et al., 2012; Schaefer et al., 2009).

The NANI approach is usually applied to medium-to-large watersheds (thousands of km^2), aggregating more highly-resolved data to estimate whole-watershed inputs, sources and sinks. Comparing the aggregate net nitrogen inputs to observed riverine N fluxes permits the inference of N retention at the watershed scale. These estimates can then be used together with hydrological and climatic variables, as well as human-derived landscape characteristics (drainage systems, dams, canals) to explore the relationships between climate, hydrology and landscape (or in-stream) N retention across watersheds (e.g. Hong et al., 2013; Howarth et al., 2012; Lassaletta et al., 2012). While some of these relationships have been examined in temperate regions, many tropical and subtropical regions remain to be studied.

Calculation of NANI requires compilation of various input datasets such as population density, livestock densities and crop production, as well as N deposition and fertilizer application rates. Availability and quality of these data can become an issue when the NANI approach is applied to regions (e.g., in developing countries) lacking well-established and standardized databases, but the relative simplicity of the method makes it an attractive option for estimating the intensity of nitrogen load to a region. Databases compiled at the global scale may be used and complement locally available information.

In this paper, we apply the NANI methodology to India, a country which has undergone significant economic development over the last few decades, with attendant stresses on its environment. With a population of 1.21 billion (2011 Census), India is second only to China in population. Its 7000 km-long coastline (CIA, 2014), and increasingly important fisheries sector (OECD/FAO, 2014) should make evaluation of the impact of nitrogen on coastal water quality a priority. Our primary goal here is to describe the calculation of NANI for India, at the country level and for major Indian watersheds, based on available information, constructing a framework that includes data sources, parameter estimation, assumptions and caveats. We also suggest possible improvements in methods for future studies, and the potential for estimating riverine N fluxes to coastal waters.

2. Methods

The area studied consists of the country of India and nine major watersheds that fall within its boundaries (Table 1). Our analyses made extensive use of publicly available spatial datasets to quantify agricultural areas and inputs, atmospheric deposition and population, as described below. GIS coverages were processed using ESRI ArcMap 10.1 (ESRI, 2011). Tabular datafiles were typically organized and processed using Microsoft Excel 2013. To delineate principal regions, GIS shapefiles of India and the boundaries of its major watersheds (Fig. 1) were obtained from the National Centre for Sustainable Coastal Management, Anna University. Areas calculated from these maps (Table 1) were used to spatially allocate variables from various datasets, available as gridded data or at different administrative units (districts), to the country and watersheds. For example, atmospheric deposition rates (mass $cell^{-1}$ $time^{-1}$) for each grid cell were summed over all grid cells within a watershed to obtain watershed totals. For regions not falling entirely within the watershed, the proportion of its area within the watershed was used to calculate the proportion of the flux falling within the watershed. Note that two watersheds, the Brahmaputra and Ganges, are shared by several countries besides India (Nepal, Bangladesh, Bhutan, Myanmar, and China). In this study, only the portions of watershed areas within India were considered in the NANI calculations (Table 1). Sources and calculations used for each component of NANI are detailed below.

Table 1
Areas (km^2) and population (nearest thousand) of major Indian watersheds (including areas within India only).

Basin	Area within India (km^2)	Percent of total area falling within India	Population (individuals)
India	3,145,460	100	1,032,689,000
Brahmaputra	195,197	30.0	34,745,000
Cauvery	83,951	100	34,756,000
Ganges	841,571	77.9	437,617,000
Godavari	312,855	100	71,018,000
Krishna	270,110	100	77,522,000
Mahanadi	138,379	100	29,475,000
Narmada	97,222	100	18,958,000
Periyar	58,785	100	39,268,000
Tapi	65,797	100	18,357,000

2.1. Estimation of atmospheric deposition of oxidized N

In NANI calculations, atmospheric N deposition typically includes only the oxidized species of N, assuming that most of the ammonia emitted from sources within a watershed is redeposited relatively close to the source within the same watershed (Howarth et al., 2006). Modeling studies estimating N deposition at a global scale include for example Dentener et al. (2006) available as a 5° (longitude) × 3.75° (latitude) gridded map, or Lamarque et al. (2010) with the resolution of 2.5° × 1.895°. Here we used multimodel-average deposition estimates from Lamarque et al. (2013) to estimate oxidized N deposition (Fig. 2) because of its higher resolution (0.5° × 0.5°).

2.2. Estimation of fertilizer N application

Fertilizer N consumption was obtained from data tables of the Fertilizer Association of India (Chanda et al., 2001). The data represent district-level fertilizer consumption for the year 2000. Fertilizer N consumption in India at the district level is shown in Fig. 3. The year 2000 data were selected to be consistent with the other data used to estimate NANI. Data for the year 2011 were used to also estimate decadal watershed-scale changes in fertilizer consumption (Table A9, supplemental material; Chanda et al., 2012).

2.3. Estimation of agricultural N fixation

Agricultural N fixation was calculated as the sum of pasture N fixation, N fixation by its major leguminous crops (soybean, groundnuts, dry beans, chickpeas and pigeon peas) and crops with endogenous etc, rice and sugar cane (Table 2). Pasture and crop areas in India and major Indian watersheds were estimated from the global map of agricultural lands created by Ramankutty et al. (2008), publicly available at http://www.geog.mcgill.ca/~nramankutty/Datasets/Datasets.html at 5 minute resolution in latitude by longitude. After obtaining pasture area, an area-based fixation rate of 1500 kg-N km^{-2} yr^{-1} was assumed, as applied by Boyer et al. (2002) for the US. Of the crops selected as significant in India, two (soybean and groundnuts) were regarded as significant N-fixing leguminous crops nationally, and three others (chickpea, dry beans and pigeon peas) were regionally important. Rhizobial N fixation by leguminous crops, as well as fixation by cynanobacterial associations in rice and by endophytic and free-living bacteria in sugar cane were estimated on a watershed area basis as the product of typical average N fixation rate per area of crop production, kg N km^{-2} yr^{-1} (Herridge et al., 2008) and the proportion of the crop production area falling in each watershed (Table A7) as determined in Monfreda et al. (2008).

2.4. Estimation of the components of NFF

2.4.1. Human N consumption

Human N consumption was estimated as population density (persons km^{-2}) multiplied by human N intake rate (kg-N $capita^{-1}$ yr^{-1}). Population in 2001 at the district level was

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