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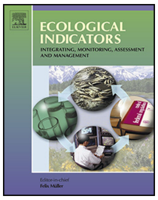

Aggregating land use quantity and intensity to link water quality in upper catchment of Miyun Reservoir

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ABSTRACT

Eutrophication resulting from nutrient enrichment decreases water quality and harms ecosystem structure and function, and its degree is significantly affected by land use in the catchment. Quantifying the relationship between eutrophication and land use can help effectively manage land use to improve water quality. Previous studies principally utilized land use quantity as an indicator to link water quality parameters, but these studies lacked insight into the impact of land use intensity. Taking the upper catchment of Miyun Reservoir as a case study, we developed a method of aggregating land use quantity and intensity to build a new land use indicator and tested its explanatory power on water quality. Six nutrient concentrations from 52 sub-watersheds covering the whole catchment were used to characterize the spatial distribution of eutrophication. Based on spatial techniques, empirical conversion coefficients, remote sensing data, and socio-economic statistical data, land use intensity was measured and mapped visually. The new land use indicator was calculated and linked to nutrient concentrations by Pearson correlation coefficients. Results demonstrated that our new indicator incorporating intensity information can quantify the different nutrient-exporting abilities of different land use areas. Compared to traditional indicators that only incorporate land use quantity, most Pearson correlation coefficients between the new indicator and water nutrient concentrations increased. This new information enhanced the explanatory power of land use on water nutrient concentrations, and so will be able to help us understand the impact of land use on water quality and guide decision making for better land use management.

1. Introduction

Increasingly serious water pollution threatens human health and survival. Eutrophication, resulting from nutrient enrichment (phosphorus and nitrogen), is one of the major challenges of water pollution control (Carpenter et al., 1998; Smol, 2008). It decreases water quality for both human consumption and amenity use (Carpenter et al., 1998), and causes intensive biological activity that typically leads to dramatic changes in the composition and structure of aquatic food webs (Dodds et al., 2008; Smith et al., 2006). Water nutrients are closely related to land use, including such broad categories of human activity as urbanization, agriculture, industry, and sewage. Quantifying the relationship between eutrophication and land use, and evaluating the impact of land use on water nutrients, would help improve land management and water quality.

Previous studies have addressed the general relationships between land use and water nutrients. Urbanization results in an increase in built-up land and impervious surfaces, which then further change the runoff process and cause water pollution (Johnes, 1996; Johnson et al., 1997; Pratt and Chang, 2012; White and Greer, 2006). Arable land, which is characterized by agricultural activities that export phosphorus and nitrogen, makes a large contribution to nutrients in the water (Ahearn et al., 2005; Broussard and Turner, 2009; Fisher et al., 2006; Mander et al., 2000b; Motavalli et al., 2008). Conversely, forested land can trap and filter water pollutants and improve water quality (Brett et al., 2005; Galbraith and Burns, 2007; Lopez et al., 2008; Postel and Thompson, 2005).

These earlier studies, however, primarily examined the quantitative structure of land use (Ahearn et al., 2005; Brett et al., 2005; Broussard and Turner, 2009; Detenbeck et al., 1993; Johnson et al., 1997; Mander et al., 2000b; Teixeira et al., 2014; Zhao et al., 2015), and did not consider the intensity of land use. Using only the quantitative proportion of land use within sub-watersheds to explain water pollution parameters between sub-watersheds has given rise to many differences among previous studies (Ahearn et al., 2005;

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Brett et al., 2005; Broussard and Turner, 2009; Detenbeck et al., 1993; Johnson et al., 1997; Mander et al., 2000b). It leads to a confused understanding of how land use influences water nutrients and leads to difficulties in water pollution management and control.

Although researchers have realized the impact of land use intensity on earth systems, few studies exist that quantify and measure land use intensity (Erb, 2012). Even with similar land use proportions, different land use intensities may result in a wide range of water quality parameters (Dillon and Kirchner, 1975; Oni et al., 2014). Previous limited studies often subsumed different land use intensity levels under the same land use type (Carey et al., 2011; Jarvie et al., 2010; Palmer-Felgate et al., 2009; Vogt et al., 2015). Furthermore, several indicators related to land use intensity are linked to water quality, such as fertilizer application (Iital et al., 2010; Mander et al., 2000a), livestock density (Berka et al., 2001; Harding et al., 1999), output of livestock product (Smith et al., 2013), population density (Yin et al., 2005), impervious surfaces (Brabec et al., 2002; Lee and Heaney, 2003), urban form (Liu et al., 2012), and so on. Also, the export coefficient model employed in previous studies used land use, fertilizer, stock rate, and human population to estimate the nutrient loadings (Johnes, 1996; Worrall et al., 2012). However, these studies separated the quantity and intensity of land use at different spatial scales.

Little is known about the joint impact of land use quantity and intensity, including the quantitative structure of different land use types and the intensity within the same land use type. A lack of quantitative knowledge about aggregating these two factors can lead to statistical bias and a poor understanding of how land use influences water quality, and so lead to difficulties in decision making and land use management. To explore the relationship between land use and water quality, a comprehensive quantification of land use information is needed. The objective of this study is as follows: (1) to propose a method for aggregating land use quantity and intensity data to build a new land use indicator; and (2) to examine the relationship between water quality and the new land use indicator.

2. Materials and methods

2.1. Study area

Miyun Reservoir, which is the main surface source of drinking water for Beijing, is located about 100 km north of that city. Its upper catchment, including two major rivers (Chao River and Bai River), is located roughly between 40°19′–41°38′ N latitude and 115°25′–117°35′ E longitude (Fig. 1). Water eutrophication in the upper catchment of Miyun Reservoir exhibits a significantly increasing trend (Li et al., 2013), and this calls for effective control and management of water eutrophication.

The catchment covers an area of 15,788 km^2 and lies within the warm, semiarid monsoon climate zone with a mean annual temperature of 9–10 °C and a mean annual precipitation of 489 mm. Precipitation from June to September accounts for 80–85% of the total annual precipitation. Elevations range from 65 to 2300 m. According to the Genetic Soil Classification of China (Shi et al., 2006), cinnamon soil, brown soil, meadow soil, and chestnut soil are the four principal soil types in the study area. The catchment includes Yanqing County, Huairou District, and Miyun in Beijing, and Fengning, Luanping, Chicheng, Chengde, Guyuan, and Chongli in Hebei Province.

2.2. Water sample collection and analysis

Water samples were collected and analyzed by the authors. Based on digital elevation data provided by the global topography database (http://www.gscloud.cn/) with a spatial resolution of 30 m, we used the hydrological analysis tool in ArcGIS 10.1 (ESRI Inc., USA) to delineate sub-watersheds. The flow accumulation threshold is a key parameter to run the tool. Coupled with a field survey in the catchment, we excluded several sub-watersheds with drying up rivers. Within the nested structure of sub-watersheds, the boundary of the headriver sub-watershed was delineated by simulating the flow path of each grid to the corresponding monitoring sites in the headriver areas using the D8 method (O'Callaghan and Mark, 1984). Then the boundary of next head sub-watershed was delineated similarly but excluded the upstream sub-watersheds. Finally, we delineated 52 sub-watersheds and set monitoring sites near the outlet of each of these sub-watersheds (Fig. 1).

Rainfall is generally viewed as the driver of runoff yield, causing pollutants to flow into watercourses. Runoff is a medium of nutrients. As precipitation in the rainy season accounts for 80–85% of the total annual precipitation, we assumed most nutrients flow into the watercourses and the Reservoir during this period. We therefore collected monthly water samples from the monitoring sites in the 52 sub-watersheds from July to September in 2013 to characterize water nutrient status in the different sub-watersheds. Excluding several rivers that were temporarily dry, we collected 48, 52, and 51 water samples in July, August, and September, respectively. Water samples were collected using 600 ml polyplastic containers and sulfuric acid was added to stabilize the nutrients in the water samples during storage. Water samples were taken to the laboratory for chemical analysis the day after collection.

Six water quality variables were analyzed from the 52 monitoring sites to fully characterize the water eutrophication status in the upper catchment of Miyun Reservoir. Total nitrogen (TN), nitrate nitrogen ($NO_3{}^-$-N), ammonium nitrogen ($NH_4{}^+$-N), and total phosphorus (TP) were quantified to study inorganic pollution; and chemical oxygen demand (COD) and biological oxygen demand during 5 days (BOD_5) were characterized to study organic pollution. Chemical analyses adhered to the national quality standards for surface water in China (GB3838-2002) as follows: TN, alkaline potassium persulfate digestion coupled with ultra-violet spectroscopy (Rice et al., 2012); $NO_3{}^-$-N, ultraviolet spectrophotometry (Rice et al., 2012); $NH_4{}^+$-N, Nessler's reagent spectrophotometry (Rice et al., 2012); TP, ammonium molybdate spectrophotometric method (Rice et al., 2012); COD, potassium dichromate titration method (Rice et al., 2012); and BOD_5, dilution and seeding method over five days (Geneva, 2003).

2.3. Land use classification

Landsat-8 Operational Land Imager (OLI) images were chosen to map land use within the upper catchment of Miyun Reservoir in 2013. Preprocessing included geometric correction, atmospheric correction, and image fusion. A digital elevation model (DEM) with 50 ground control points, which were taken from 1:50,000 topographic maps (provided by the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences), was incorporated in the geometric corrections; this resulted in a root-mean-square spatial positioning error of less than 0.5 pixels for each image. The FLAASH module from the Environment for Visualizing Images (ENVI) software was used for atmospheric corrections. The Gram-Schmidt Pan Sharpening module was used for fusion of multispectral and panchromatic satellite images.

Land use was mapped by visual interpretation into eight categories, including arable land, forest, grassland, water body, residential land, industrial and mining land, road, and unused land. The land use map was resampled with a spatial resolution of 30 m in