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Spatiotemporal modeling of watershed nutrient transport dynamics: Implications for eutrophication abatement

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ABSTRACT

The main objective of this study was to quantify nutrient transport dynamics of a previously ungauged, temperate watershed (145 km^2) surrounding a shallow eutrophic lake and discern lake response to external nutrient loading, based on soil water assessment tool (SWAT) and the Organization of Economic Cooperation and Development (OECD) empirical lake models, respectively. A SWAT model was used to simulate baseline nutrient dynamics after its calibration and validation against daily tributary flow, total dissolved phosphorus (TDP), total phosphorus (TP), and nitrate (NO_3) loads. On the watershed scale, median annual TDP, TP, and NO_3 losses were 0.4, 1.1, and 2.0 kg ha^{-1}, respectively. The highest median annual TP and NO_3 losses were estimated at 3.7 and 7.7 kg ha^{-1} for pastureland and 1.7 and 3.8 kg ha^{-1} for cropland and mixed forests, respectively. Baseflow was the major nutrient transport pathway over a wide range of precipitation events (450 to 900 mm yr^{-1}). Erosion was the predominant surface process exporting P across the watershed. Critical source areas (CSAs) of TP and NO_3 comprised 17% and 4% of the watershed, respectively. Annual mean TP, and mean and maximum chlorophyll content indicated a hyper-eutrophication risk for the lake. An external P load reduction by excess of 80% could be necessary to restore mesotrophy in the lake. Our results suggested that subsurface P transport should not be overlooked a priori when groundwater-dependent and extensively farmed watersheds are managed for eutrophication abatement.

1. Introduction

Lake eutrophication is a globally widespread issue adversely affecting environmental quality and socio-economic well-being of communities that depend on lake ecosystems (Pretty et al., 2002; Le et al., 2010). Watershed modeling is a powerful tool that can provide an insight of the spatiotemporal nutrient dynamics and the mechanisms driving them. The information provided by watershed models is instrumental for making ecologically and economically sound management decisions that can ultimately restore water quality in eutrophic lakes.

Soil water assessment tool (SWAT) is a semi-distributed, mechanistic model used worldwide for studying spatiotemporal contaminant dynamics (Scott et al., 2008; Winchell et al., 2013). Modelers can conveniently use the geographical information system (GIS) interfaces (e.g., ArcSWAT) and create a SWAT model for an area of interest based on the availability of digital elevation model (DEM), soil, and land use/land cover (LULC) data. In Turkey, SWAT was used to model water flow in the watersheds of Porsuk (5649 km^2) (Gungor and Goncu, 2013) and Melen streams (2437 km^2) (Akiner and Akkoyunlu, 2012), Köyceğiz-Dalyan lagoon (69 km^2) (Erturk et al., 2014), watershed nutrient dynamics of Lake Beyşehir (Beklioglu et al., 2014), Lake Ulubat (Bulut and Aksoy, 2008) and Köyceğiz-Dalyan lagoon (Ekdal et al., 2011). Using a scenario analysis, Bulut and Aksoy (2008) assessed the potential spatial response of P loss to fertilizer application rates in Lake Ulubat watershed. Beklioglu et al. (2014) provided a detailed account of calibration, validation, and sensitivity analysis for modeling soluble reactive P and nitrate (NO_3).

Smallest spatial components of SWAT are hydrologic response units (HRUs). High nutrient-yielding HRUs can be used for the identification of critical source areas (CSAs). To our knowledge, a limited number of studies exploited the CSA identification capabilities of SWAT (e.g. Winchell et al., 2014). SWAT-based delineations of CSAs on a watershed scale of different magnitudes from 30 km^2 to 3100 km^2 were carried out using an inverse modeling (IM) method for Lake Wister in USA (Busteed et al., 2009), Lake Champlain in Canada and USA (Winchell et al., 2014), and Lake Erhai in China (Shang et al., 2012). The following conclusions are derived from previous studies: (1) CSAs constituting less than ca. 25% of the lake watersheds delivered more than ca. 70% of diffuse total phosphorus (TP) load; (2) croplands and pastures with steep slopes

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and less permeability were CSAs of phosphorus (P); and (3) CSAs of nitrogen (N) were not as spatially concentrated as those of P (Busteed et al., 2009; Ghebremichael et al., 2010; Winchell et al., 2014).

One of the practical and reliable tools to quantify effects of external nutrient loading on trophic indicators (e.g. in-lake TP, chlorophyll, and Secchi depth) and state (e.g. mesotrophic and eutrophic) of lakes is the simplified P load-lake response models developed in the scope of international eutrophication program of the Organization of Economic Cooperation and Development (OECD) (OECD, 1982; Rast and Thornton, 2007). These empirical models were validated using data from more than 200 lakes worldwide which predicted mean annual TP, mean and maximum annual chlorophyll, mean annual Secchi depth, and areal hypolimnetic oxygen depletion with a reasonable accuracy for temperate, tropical, and subarctic lakes (Rast and Lee, 1983; Walmsley and Thornton, 1984). The five-level boundary trophic classification system developed by the OECD eutrophication program was used through which a single trophic category (fixed boundary) or a number of probable trophic categories (open boundary) can be assigned to a lake using in-lake TP, chlorophyll, and Secchi depth (Rast and Thornton, 2007).

The objective of this study was to (1) quantify watershed-scale diffuse sources and export dynamics of nutrients, (2) predict the response of a shallow eutrophic lake (Lake Yeniçağa, Turkey) to external nutrient loadings, and (3) identify potential CSAs in a previously ungauged watershed using SWAT and the OECD empirical models.

2. Methods

2.1. Study area

Lake Yeniçağa (latitudes 40.71–40.85 N and longitudes 31.90–32.19 E) is a shallow, temperate, and eutrophic lake located in the western Black Sea watershed of Turkey. Surface area of the lake is 2.42 km^2; its average and maximum depths are 1.6 and 4.5 m, respectively. Perennial tributaries of the lake are Hamzabey, Güzveren, Kaymaz, and Aksu streams. Kınalı (Adaköy) tributary is ephemeral and other three ephemeral streams (Ömerli, Kirenli, and Fındıklı) are mainly concentrated in the urbanized southern shore of the lake.

The lake watershed, which constitutes the study area, is 145 km^2. Average elevation of the watershed is 1175 ± 148 m above sea level. According to 2012 census figures, population density of the study area was 42 people km^{-2}. Land use and land cover (LULC) of the watershed changed significantly between 1944 and 2009 with forests and agricultural land encompassing 56 and 42% of the watershed, respectively (Evrendilek et al., 2011).

2.2. Field monitoring

Perennial lake tributaries of Aksu, Güzveren, Hamzabey, and Kaymaz were monitored for 10 months (September 2011 to July 2012). Aksu and Kaymaz stations were very close to the lake, whereas Güzveren and Hamzabey stations were situated away from the shore since the lake inlets were inaccessible for routine monitoring. Manual water sampling and flow measurement were performed a minimum of three days per month between September 2011 and June 2012. The tributaries were manually monitored once in July 2012 (July 18) before the monitoring campaign was concluded. Flow rate measurements were performed using a handheld acoustic Doppler velocimeter (FlowTracker; SonTek, San Diego, USA). Grab water samples were collected using screw-cap plastic bottles and transported to the laboratory in cooler chests on the same day for the subsequent analyses. The samples were kept refrigerated until their analyses were complete.

Two stations on Aksu and Hamzabey streams were used for automated water sampling and flow measurement (Sigma 950 AV & SD900; Hach Lange GmbH, Dusseldorf, Germany). Stream water was automatically sampled every 24 h depending on water availability. Automatic flow measurements were cross-checked against manual data and corrected when necessary. Data obtained via automatic and manual methods at Aksu and Hamzabey stations were merged to generate the observation dataset used for calibrating the SWAT model.

Lake water column was sampled using a 15-station grid on 10 different dates spanning the water year of 2012 (Oct. 1, 2011–Sep. 30, 2012). The samples were obtained with a Van Dorn horizontal sampler, stored in 1-L polypropylene screw-cap bottles and transferred to the laboratory on the sampling day for the analyses.

Atmospheric nutrient deposition was monitored using two custom-built wet/dry samplers. One sampler was placed to the east of the lake, while the other one was situated on the south-west shore. Before the initiation of each sampling period, deposition collectors were washed with deionized water (15 MΩ cm) several times until conductivity of the rinse water was ≤1.5 μS cm^{-1}. The samplers were routinely checked on a weekly basis and also after storm events. The wet deposition samples were transported to the laboratory immediately upon their detection. Mean NO_3 concentration was determined using two simultaneous samples and a precipitation-weighed concentration was calculated for the monitoring period.

2.3. Laboratory analyses

Sample aliquots were filtered using 0.45-μm membrane filters (Millex-HV). The filtrates were used for dissolved reactive P (DRP), TDP, and NO_3 analyses. Total N and TP of the samples were determined in representative unfiltered aliquots. Persulfate method described by Ebina et al. (1983) was used for simultaneous N and P digestion. Analytes were determined using the standard spectrometric methods (Eaton et al., 2005); all the measurements were made using a UV/Visible spectrophotometer (DR 5000; Hach Lange, Dusseldorf, Germany).

2.4. Model description

The model was constructed using ArcSWAT 2012.10.14 installed in ArcMap 10.1 (ESRI, 2012; Stone Environmental Inc., 2013; Winchell et al., 2013). SWAT parameters, notation for variables used, and their descriptions henceforth conform to Arnold et al. (2012b). We revised SWAT2012 (rev. 627) code to debug *latsed.f* routine (Eq. A.1).

2.4.1. Topography and drainage

Watershed was delineated using a 10 × 10 m digital elevation model (DEM) and eight flow direction matrix method (Jenson and Domingue, 1988; Map General Headquarters, 2011). Drainage network obtained using DEM was further improved manually via an ArcMap satellite imagery base map. Fifteen subbasins were created using a minimum drainage area of 500 ha (Fig. 1), and henceforth, each subbasin is called with its unique number preceded by S for brevity. Multiple SWAT subbasins constituted the drainage basins of Güzveren, Hamzabey and Kınalı tributaries, whereas the drainage basins of Aksu and Kaymaz tributaries were represented by single SWAT subbasins as S12 and S14, respectively. Due to their small drainage areas, Fındıklı, Ömerli, and Kirenli ephemeral streams in S10 were excluded in the synthetic drainage network. Subbasin 6 and S8 with an overall area of 2.5 km^2 were excluded in analyses of lake external nutrient load, and CSAs because they were located downstream of the lake. Subbasin characteristics of the lake catchment are given in Table 1.

2.4.2. Land use and land cover

CORINE land cover 2006 data of the study area was used in the model (European Environment Agency, 2016). CORINE LULC classes were converted to the SWAT classes (Table B1) (Commission of the European Communities, 1995; Arnold et al., 2012b). In descending order, following SWAT LULC classes each constituted more than 10% of the lake catchment: FRSE (24.30%), AGRL (24.29%), and AGRC (16.79%). Upon an analysis of the agricultural land use statics, AGRL