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Determination of unit nutrient loads for different land uses in wet periods through modelling and optimization for a semi-arid region

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SUMMARY

Diffuse pollution abatement has been a challenge for decision-makers because of the intermittent nature and difficulty of identifying impacts of non-point sources. Depending on the degree of complexity of the system processes and constraints related to time, budget and human resources, variety of tools are used in diffuse pollution management. Decision-makers prefer to use rough estimates that require limited time and budget, in the preliminary assessment of diffuse pollution. The unit pollution load method which is based on the pollution generation rate per unit area and time for a given land use can aid decision-makers in the preliminary assessment of diffuse pollution. In this study, a deterministic distributed watershed model, SWAT is used together with nonlinear optimization models to estimate unit nutrient pollution loads during wet periods for different land use classes for the semi-arid Lake Mogan watershed that is dominated by agricultural activities. Extensive data sets including in-stream water quality and flowrate measurements, meteorological data, land use/land cover (LULC) map developed using remote sensing algorithms, information about agricultural activities, and soil data are used to calibrate and verify the hydraulic and water quality components of SWAT model. Results show that the unit total nitrogen (TN) and total phosphorus (TP) loads (0.46 kg TN/ha/yr and 0.07 kg TP/ha/yr) generated from the watershed during wet periods are very close to the minimum values of the loads specified in the literature and highly depend on the variations in rainfall. Estimated unit nutrient loads both at watershed scale and for different land use classes can be used to assess diffuse pollution control measures for similar regions with semi-arid conditions and heavy agricultural activity.

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1. Introduction

Current water resources management policies require assessment of all the pressures such as climate change, point and non-point sources, and urbanization on water resources to develop sustainable strategies. Because of stringent regulations, progress on control of point sources is faster than that of diffuse pollution. The intermittent nature of diffuse pollution makes it more difficult to monitor and control compared to point sources. Unlike point source pollution, monitoring of diffuse source pollution at the source of origin is difficult or even impossible. Decision-makers often use watershed models supported by extensive water quality monitoring companions to assess diffuse pollution and evaluate the effectiveness of management alternatives to mitigate impacts of diffuse pollution on the environment. In order to select the most suitable model in water resources management, it is important to consider data availability, capability of the model to simulate design variables, accuracy, and temporal and spatial scales (Singh and Frevert, 2006).

Even though models are powerful tools that can be used in developing water resources management plans, there are situations such as preliminary assessment or prioritization of the pollutants where decision-makers can prefer other approaches which require less time, budget and human resources. These methods such as unit pollution load approach can still yield robust results depending on the required accuracy level. Unit pollution load which is an export coefficient, is a value that represents pollution generation rate per unit area per time for each land use class or averaged over a small basin (Novotny, 2003). Pollution load export coefficients are multiplied by the contributing areas that represent specific land use classes to estimate total pollution load generated from a given catchment. The most common dimension of unit load is mass/area/time. Caruso et al. (2013) suggested that unit nutrient loads from agricultural areas can be used in conjunction with

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integrated catchment modelling to evaluate impacts of future land use changes on water quality. On the other hand, unit pollution loads are highly site specific and depend on demographics, geographic and hydrologic factors as Novotny (2003) stated. There have been several literature survey studies that summarize the unit pollution loads (Limnotech, 2007; Lin, 2004; Novotny, 2003; US EPA, 1999) from various land use and crop types. A summary of unit pollution loads from different land use/land cover classes (LULC) are given in Table 1.

As depicted in Table 1, the unit pollution loads can vary by two orders of magnitude for the same LULC class and even for the same crop type. In the literature, the unit loads are presented for specific LULC classes and are based mostly on modelling and/or monitoring studies. In addition, the unit load values given in the literature usually focus on a year-round average rather than a specific climatic condition such as dry/wet weather periods. If decision-makers use these unit load values in any diffuse pollution management plan, a detailed meta-analysis has to be conducted to select the correct unit pollution load values that can represent the meteorological, LULC, crop type and topography same as the study area.

In this study, total and unit diffuse pollution loads for Total Nitrogen (TN), Total Phosphorus (TP), and Total Suspended Solids (TSS) at the sub-watershed scale are estimated using (i) water quality measurements, (ii) water quality estimations obtained from the calibrated SWAT model, and (iii) literature values. Then, in an attempt to calculate contributions of different land use classes (i.e., residential, agriculture, fallow, pasture, other) to unit TN load, a non-linear optimization problem is formulated and solved. Unit nitrogen loads for each land use class are selected as the decision variables of the optimization model. Total nitrogen load of a sub-basin can be estimated by multiplying the unit nitrogen loads for each land use class by the corresponding areas of each land use class within that sub-basin. The objective function is to minimize the sum of the errors, between total nitrogen load estimated from the calibrated SWAT model and total nitrogen load estimated using unit nitrogen loads (i.e., decision variables) for each land use class, for a selected number of sub-basins. Another non-linear optimization problem is formulated and solved to estimate unit phosphorus loads for each land use class. The proposed approach is demonstrated on Yavrucak sub-basin of Mogan Watershed for wet periods. Unit diffuse pollution loads for TN and TP generated from different land use classes can aid decision-makers in developing cost-effective management strategies. It is aimed that the outcomes will contribute to the literature in terms of unit pollution loads generated during wet periods calculated both on the basis of watershed area and different land use classes for the regions similar to the study area.

2. Material and methods

In this study, a deterministic distributed watershed fate and transport model, SWAT, together with optimization techniques are used to estimate unit nutrient pollution loads during wet periods for different land use classes for the semi-arid Lake Mogan watershed dominated by agricultural activity. The flowchart of the methodology used in this study is depicted in Fig. 1. Firstly, extensive data sets are used to develop the SWAT model of the selected case study area (i.e., Lake Mogan watershed) and unit pollution loads (TN, TP, TSS) are calculated at the Yavrucak monitoring station. The unit pollution loads (TN, TP, TSS) calculated in a sub-watershed scale are compared with the measured and literature values. Then contributions of different land use classes to unit TN and TP loads are estimated using non-linear optimization and the outcomes are compared with the literature values. In the following sub-sections, information about the study area, SWAT model description and calibration procedure and finally the mathematical formulation of the optimization model are provided.

2.1. Study area

Lake Mogan which was declared a Specially Protected Area in 1990 is located in the Gölbaşı District, located 20 km south of Ankara metropolis. There are 30 settlements in the Lake Mogan

Table 1
Unit pollution loads calculated in various studies.

Reference	Description	Total Phosphorus (kg/ha/yr)	Total Nitrogen (kg/ha/yr)
Agriculture			
MPCA (2004a)	Dry season/Normal season/Wet season	0.18–0.22/0.38–0.39/0.69–0.70	
Robertson (1996)	Small watershed/Large watershed	3.13/0.4	
Novotny (2003)	Min.; Max.	0.10; 10	0.80; 70
Forest			
MPCA (2004b)	Deciduous – temporary	0.075	
US EPA (1999)	Min.; Max.	0.10; 0.13	1.1; 2.3
Robertson (1996)		0.1	
Kunimatsu et al. (1999)		0.133	
Novotny (2003)	Min.; Max.	0.03; 0.8	1; 8
Pasture/Meadow			
MPCA (2004b)		0.169	
US EPA (1999)	Min.; Max.	0.01; 0.25	1.2; 7.1
Novotny (2003)	Min.; Max.	1. 0.7	5; 11
Residential			
Mcfarland and Hauck (2001)		2.23	0.6
MPCA (2004c)	Low–High density Commer./Industry/Transport.	0.88–0.9/1.11–1.19/1.45–1.55	
US EPA (1999)	Min.; Max.	0.46; 0.81	3.3; 6.6
Novotny (2003)	Min.; Max.	0.40; 8	7; 90
Golf Course			
MPCA (2004c)	Urban meadows	0.88–0.94	
Watershed Protection and Development Review Department (2005)		4.38–8.76	
Kunimatsu et al. (1999)		3.04	
King et al. (2001)	Turf	0.27–0.66	

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