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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.

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	

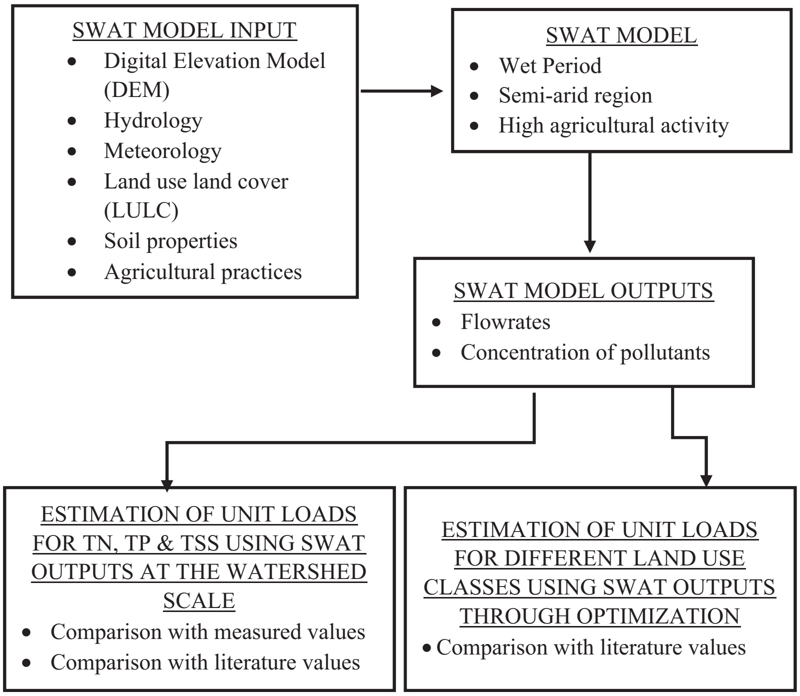

Fig. 1. Schematic representation of the methodology used in this study.

watershed and the total population is approximately 120,000. The watershed (Fig. 2) has a total drainage area of 970 km^2 with elevations ranging from 960 to 1700 m. The slopes in the region are low, mostly ranging between 1% and 10%. The average depth of Lake Mogan is around 2.8 m and its average elevation from the sea level is 974 m. The lake and its vicinity is used extensively for agricultural activities. Dry farming is practiced in approximately 50% of Lake Mogan's watershed and 30% of the watershed is covered with pastures. Only 10% of the watershed is urbanized. In the basin, the most widely grown crop is grain but cultivation of vegetables is also carried out on a limited scale.

Groundwater supply to the lake is quite low, and water entry is irregular and through creeks which are usually dry in summer (DSİ, 1993). The most important creeks feeding the lake are the ones located in the east–north–west regions of the watershed, discharging into Lake Mogan: Sukesen, Başpınar, Çölova, Yavrucak, Çolakpınar, Tatlım, Kaldırım and Gölcük. Among them the Sukesen, Yavrucak, and Çölova creeks are the main inputs supplying water to the lake. The lake is substantially fed by Sukesen Creek from the northwest, by Çölova Creek from the south and by the wetland named Çökek Marsh formed by the Yavrucak and Başpınar Creeks.

When the arid conditions of the region are considered, the ecological importance of the lake stands out more. Lake Mogan as a wetland area has both ecological and recreational value. The lake is used by 227 bird species for breeding, foraging, and resting and the lake was nominated as a Ramsar site. Because of agricultural diffuse pollution and rapid urbanization, the trophic state of Lake Mogan is mostly eutrophic. Karaaslan et al. (2013) reported that agricultural areas, especially those located in the south of Lake Mogan, affect aquatic life due to fertilizer and pesticide applications. They also mentioned that the depth and volume of the lake decreased due to material moving into the lake via erosion, snow melt and surface drainage. In addition to diffuse agricultural pollution sources, water quality of the lake is being negatively affected by the growing and poorly planned urbanization around the lakeshore.

2.2. SWAT model description

The SWAT model was developed by the United States Department of Agriculture – Agricultural Research Service (USDA-ARS) with the purpose of predicting the impact of management practices on water, sediment and agricultural chemical yields in large ungauged basins. It is a conceptual model that operates on a daily time step and can simulate surface flow, subsurface flow, soil erosion, sediment deposition, and the movement of nutrients through watersheds (Arnold et al., 1998). The SWAT model has been used in many watershed modelling studies with various purposes, e.g., hydrologic assessments, climate change impacts, evaluation of best management practices, estimation of the pollution loads, determination of effects of land use change, etc. (Abbaspour et al., 2015; Benaman et al., 2007; Daggupati et al., 2015; Dechmi and Skhiri, 2013; Liu and Lu, 2014; Zhang et al., 2014; Rocha et al., 2015; Yesuf et al., 2015; Lin et al., 2015; Fan and Shibata, 2015).

To perform simulations, SWAT divides a watershed into a number of sub-basins and these sub-basins are then further divided into units having unique soil, slope and land use properties. These units are called hydrologic response units (HRUs) (Dechmi et al., 2012) and they are represented as a percentage of the sub-basin area (Arnold et al., 2012).

2.3. Model inputs, calibration and validation

In this study, ArcSWAT 2012 which is an ArcGIS extension (ArcGIS Desktop 10 Service Pack 5) was used to perform SWAT simulations. Data used in the model can be classified under 5 main categories as; topography, soil, agricultural practices, LULC, and meteorology. Information about agricultural practices, meteorology and topography were obtained from several institutions and LULC and soil maps were develop within the context of this study.

In this study, remote sensing algorithms were used to develop the LULC map using Rapid Eye satellite images. The Rapid Eye image data dated May 7th, 2013 has five spectral bands. The image

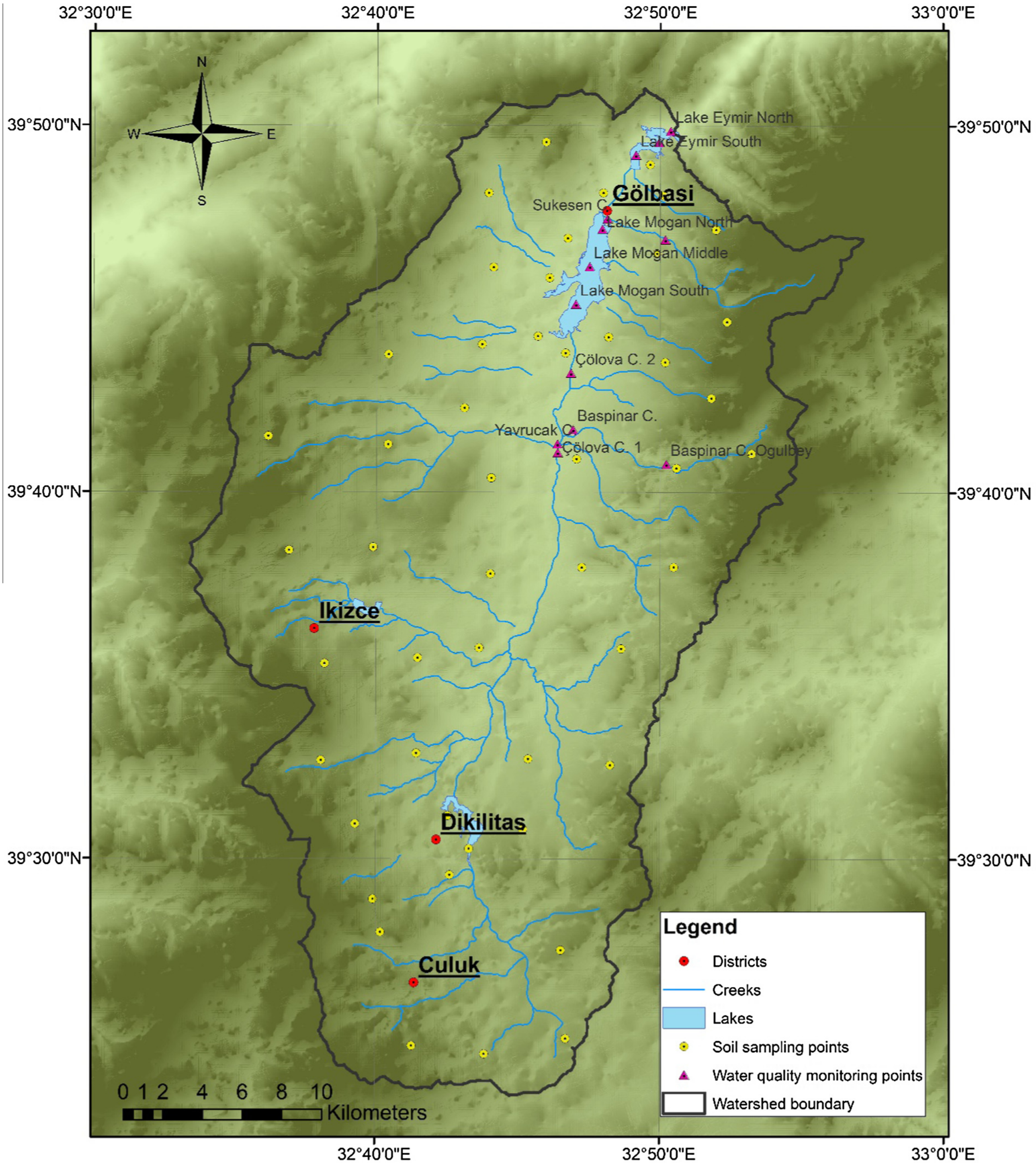

Fig. 2. Lake Mogan Watershed and the Mogan-Eymir special environmental protection region.

covers the whole study area, with a spatial resolution of 5 m. Nine LULC classes, namely, water bodies, forest, agriculture, road, settlement, mine site, fallowing land, rangeland, and bare land, were used in the classification. Total classification accuracy for the Rapid Eye image data was determined as 70%. The details of the development of the LULC map are given in Alp et al. (2014). Digital Elevation Model (DEM) and its products like slope and aspect were added to image data as additional bands to increase the accuracy. As a result, total accuracy was increased to 80%. Percent of LULC classes after classification show that the highest percentages of the LULC classes are rangeland (42%), agriculture and fallowing land (39%), and residential (10%) (Table 2 and Fig. 3).

Table 2
LULC classification of Lake Mogan watershed.

Name of the class	Ratio (%)
Water	1.2
Forest	1.9
Agriculture	30.7
Fallowing land	8.2
Road	1.9
Residential	10.4
Mine site	0.03
Rangeland	42.2
Bare land	3.5
Total	100.0

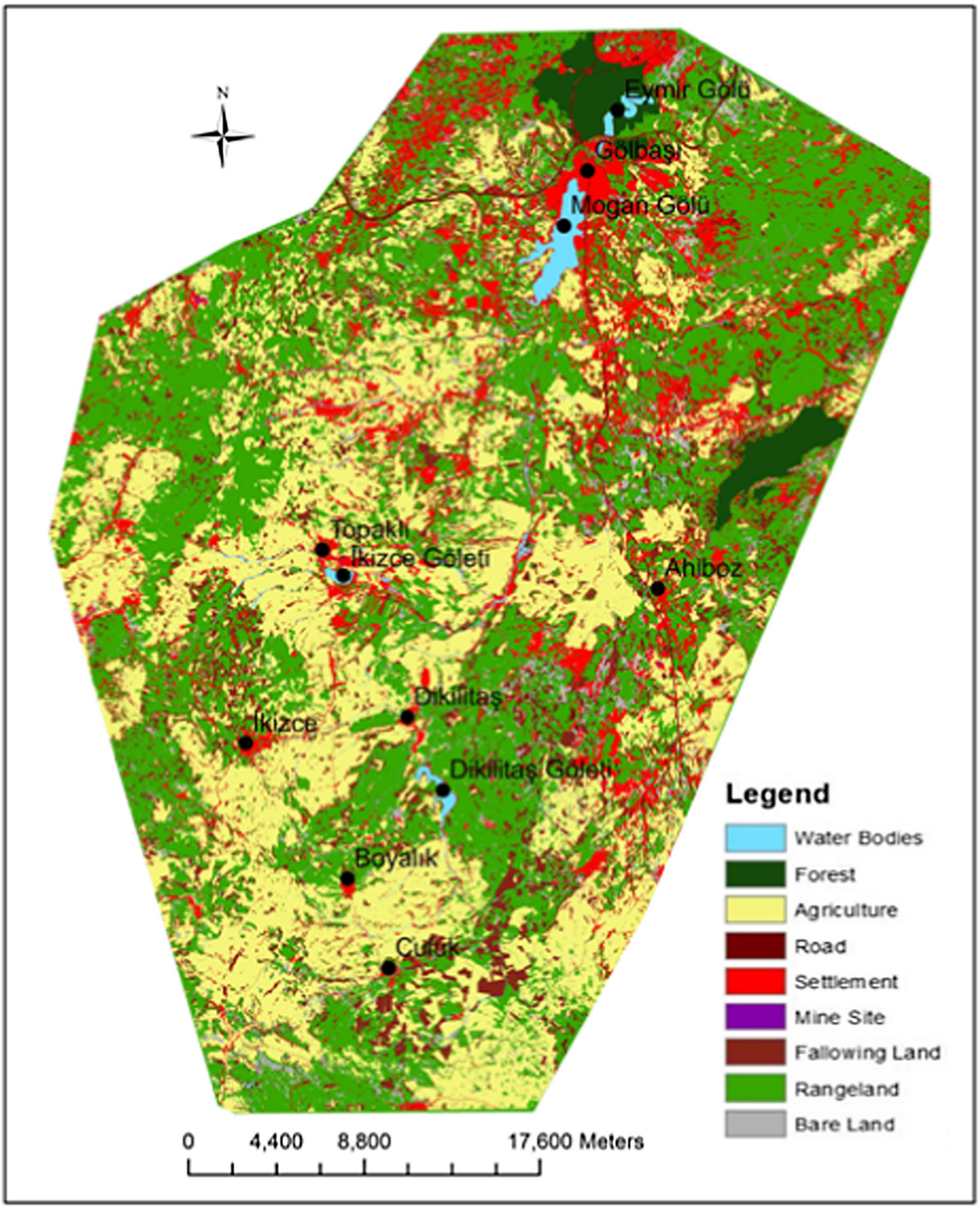

Fig. 3. Final LULC classification of Lake Mogan Watershed.

Thirty-piece vector maps in 1/25,000 scale were obtained from the Turkish General Command of Mapping to create the DEM of the whole watershed. These vector maps were used to obtain DEM by using geo-statistical interpolation methods.

Information regarding agricultural practices carried out in the watershed was acquired from Gölbaşı District Directorate of Food, Agriculture and Livestock, and the Central Research Institute of Soil Fertilizer and Water Resources. In the Mogan Watershed, dry farming is practiced and crops are planted in September, harvested between July and August and tillage is performed four times in a year. Urea, ammonium nitrate, ammonium sulfate, diammonium phosphate are the common fertilizer types applied between February–March and October depending on the type of the planted crop.

In this study, an extensive field study was carried out covering the whole watershed in 2013 and forty-nine different soil samples were collected to create the soil map of the watershed. The analysis of soil samples for physical and chemical characteristics including nutrients and 16 other parameters such as pH, organic carbon, profile depth, maximum root depth, electrical conductivity, hydraulic conductivity, clay, sand, and silt contents were performed by the Central Research Institute of Soil Fertilizer and Water Resources Laboratory. Results of the soil analysis are used to develop the spatial soil map of Lake Mogan watershed using the Thiessen Polygons method.

The meteorological input data (2007–2010) including daily precipitation, maximum and minimum daily air temperature, relative humidity, solar radiation, and wind speed were obtained from the General Directorate of Meteorology. Various water quality parameters have been measured such as pH, dissolved oxygen, total suspended solids, total nitrogen, total phosphorus, total coliforms, and chemical oxygen demand (COD) within the watershed since 2006 and were obtained from the General Directorate of Natural Heritage Protection. Monthly average flowrates of the creeks that discharge into Lake Mogan were obtained from the Limnology Laboratory at METU.

In this study, SWAT model was calibrated for the Lake Mogan watershed based on the data (2007–2010) obtained from Yavrucak monitoring station. Model validation was carried out at Sukesen monitoring station for the same period. The model was calibrated for streamflow, sediment, nitrogen and phosphorus with SWAT-CUP (SWAT Calibration and Uncertainty Procedures) which is a public domain calibration module (Abbaspour et al., 2007) for SWAT. SUFI-2 uncertainty analysis of SWAT-CUP was used in this study. All sources of uncertainties, i.e., input data (e.g., precipitation), conceptual model, model parameters and observed data are taken into consideration by SUFI-2 (Abbaspour et al., 2007). In SUFI-2, model output uncertainty is quantified by the 95% prediction uncertainty (95PPU). The 95PPU is determined at the 2.5% and 97.5% levels of the cumulative distribution of an output variable which is obtained through Latin hypercube sampling (Abbaspour et al., 2007). The goodness of fit is determined by the *p*-factor and the *r*-factor. While the *p*-factor is the percentage of measured data bracketed by the 95% prediction uncertainty, *r*-factor is the average thickness of the 95PPU band divided by the standard deviation of the measured data. An ideal model simulation in which 100% of the observed data is bracketed within the model prediction uncertainty is with a *p*-factor of 1 and *r*-factor of 0 (Abbaspour et al., 2007, 2015).

Model performance was evaluated using time series graphics, and several statistical criteria including Nash–Sutcliffe simulation efficiency (NSE), coefficient of determination (R^2), and percent bias (PBIAS). After streamflow calibration, sediment and water quality calibration was performed. For sediment calibration, monthly total suspended solids (TSS) measurements, and for water quality, monthly total nitrogen (TN), nitrate (NO_3), and total phosphorus (TP) measurements at Yavrucak monitoring station were utilized. Additional information about the model input and model calibration process can be found in Alp et al. (2014).

2.4. Unit pollution load estimation through non-linear optimization

Two different nonlinear programming models, one for nitrogen and one for phosphorus, are formulated and solved to estimate unit pollution loads for different land use classes. The following objective function for the nonlinear optimization model is used for determining unit loads for nitrogen:

$$Min.\,Z = \sum_{i=1}^{k}\left[\frac{1}{A_i}\left(\left(\sum_{j=1}^{l}UNL_jA_{ij}\right) - NL_i\right)^2\right] \quad (1)$$

where i is the index for sub-basin, k is the total number of sub-basins, j is the index for land use class, l is the total number of land use classes, A_i is the total area of sub-basin i (ha), UNL_j is the unit nitrogen load for land use class j (kg/ha/yr), A_{ij} is the area of land use class j in sub-basin i (ha), NL_i is the total nitrogen load for sub-basin i calculated by SWAT (kg/yr). UNL_j, $j = 1,2,3,\ldots,l$, are the decision variables of the optimization model. A similar optimization problem is formulated for phosphorus.

3. Results and discussion

3.1. Model calibration and validation

Parameters related to snow and groundwater processes were the most sensitive parameters in streamflow calibration. The model performance was evaluated using time series graphics, NSE, R^2 and PBIAS (%) criteria. There exist no explicit standards to assess the model performance with these statistics (Santhi et al., 2001). However, for NSE and PBIAS, general performance ratings for a monthly time step are given as in Table 3 by Moriasi et al. (2007). R^2 ranges from 0 to 1 and, values higher than 0.5 are usually accepted as satisfactory (Moriasi et al., 2007). In this study, for the best simulation NSE, R^2 and PBIAS values are 0.74, 0.8 and −19.1, respectively. The statistical criteria show that the model performance is satisfactory to simulate hydrological processes (Moriasi et al., 2007). The calibration results indicate that at Yavrucak monitoring station, the measured and simulated streamflow values are in good agreement (Fig. 4). In Fig. 4, the gray areas represent 95PPU.

Table 3
General performance ratings for NSE and PBIAS for a monthly time step (adapted from Moriasi et al., 2007).

Performance rating	NSE	PBIAS (%)		
		Streamflow	Sediment	N, P
Very good	0.75 < NSE ⩽ 1.00	PBIAS < ± 10	PBIAS < ± 15	PBIAS < ± 25
Good	0.65 < NSE ⩽ 0.75	±10 ⩽ PBIAS ⩽ ± 15	±15 ⩽ PBIAS ⩽ ± 30	±25 ⩽ PBIAS ⩽ ± 40
Satisfactory	0.50 < NSE ⩽ 0.65	±15 ⩽ PBIAS ⩽ ± 25	±30 ⩽ PBIAS ⩽ ± 55	±40 ⩽ PBIAS ⩽ ± 70
Unsatisfactory	NSE ⩽ 0.50	PBIAS ⩾ ± 25	PBIAS ⩾ ± 55	PBIAS ⩾ ± 70

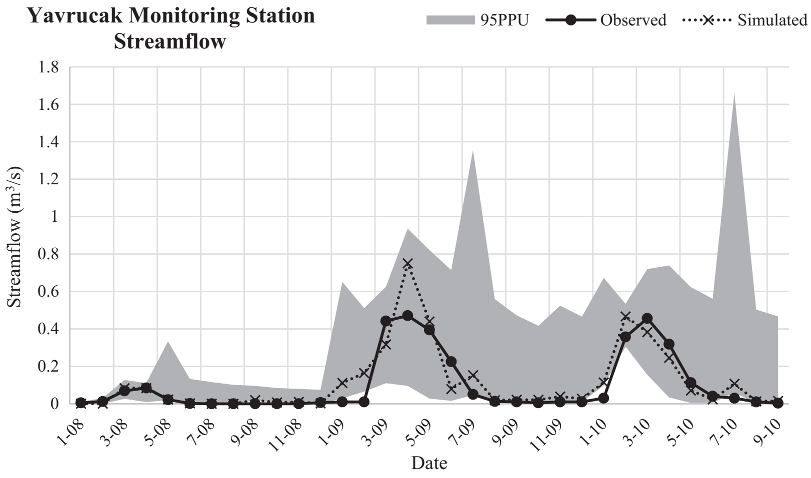

Fig. 4. Observed vs. simulated streamflow for the calibrated model at Yavrucak monitoring station with 95% prediction uncertainty.

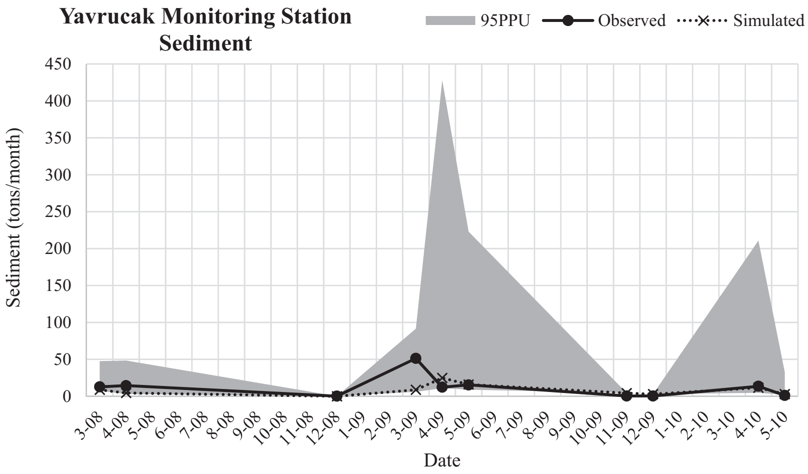

Fig. 5. Observed vs. simulated sediment load for the calibrated model at Yavrucak monitoring station with 95% prediction uncertainty.

Model sediment calibration was performed by fixing hydrology-related calibration parameters, and adjusting sediment parameters. A total of 20 parameters were used, and 1500 runs were performed. There is a reasonable agreement between the observed and simulated sediment loads (Fig. 5).

Water quality calibration was challenging due to limited data availability. 1500 runs were performed with 15 parameters. The results, given in Table 3, show that some peak loads, especially for NO_3, cannot be captured by the model. Total phosphorus loads, on the other hand, are overestimated in some months. Because of data limitations the mean values of the simulated and observed loads in the long term are compared. The results show that when the long term averaged values are of concern, model performance is satisfactory (Table 4). Therefore, the results can be used to evaluate the unit pollution loads arising from different land use classes.

For the model validation, the mean values of observed and simulated streamflow, and nutrient loads are given in Table 5. Since the validation is realized for a different watershed with different characteristics, the performance of the validation is not as good as that of the calibration. In addition, due to flowrates being significantly smaller at the Sukesen monitoring station, the pollution loads are relatively small compared to those of the Yavrucak monitoring station. For example, the observed and simulated mean flowrates at Sukesen station are 30 L/s and 10 L/s, respectively. Hence, even though the percent differences are large between the measured and the simulated flowrates and pollution loads, this difference is acceptable in terms of modelling purposes because of low values of streamflows.

Table 4
Observed and simulated mean monthly streamflow and nutrient loads at the Yavrucak monitoring station (calibration results).

	Mean		Percent relative error
	Observed	Simulated	
Streamflow (m^3/s)	0.10	0.12	20.0
Sediment (tons)	12.1	8.3	−31.4
NO_3-N (kg)	1567.1	973.7	−37.9
TN (kg)	369.4	326.1	−11.7
TP (kg)	91.3	92.7	1.5

Table 5
Observed and simulated mean monthly streamflow and nutrient loads at the Sukesen monitoring station (validation results).

	Mean		Percent relative error
	Observed	Simulated	
Streamflow (m^3/s)	0.03	0.01	−66.7
Sediment (tons)	23.9	1.8	−92.5
NO_3-N (kg)	514.9	361.7	−29.8
TN (kg)	55.3	112.9	104.2
TP (kg)	6.2	14.2	129.0

3.2. Unit pollution loads for Lake Mogan Watershed

Within the scope of this study, first, pollution loads (TN, TP, TSS) were calculated at the Yavrucak monitoring station for the corresponding sub-watershed and are presented in Section 3.2.1. Secondly, unit pollution loads for different land uses (agriculture, residential, etc.) were estimated at the same monitoring station using non-linear optimization and are presented in Section 3.2.2.

The unit pollution loads were calculated at Yavrucak monitoring station since this sub-basin is more representative of the whole Lake Mogan watershed. While Yavrucak subbasin is mostly covered with agricultural lands (47%), pastures as well occupy a significant part (31%) of the basin. The subbasin is flat, and only 2% of the total area has a slope higher than 10%. The location and land use percentages of Yavrucak subbasin are shown in Fig. 6 and Table 6, respectively.

3.2.1. Unit pollution loads at the sub-watershed scale

In the following subsections the calculation of unit pollution loads were performed using three different methods. First, the unit pollution loads were calculated by using the water quality measurements at the Yavrucak monitoring station. In the second method, calibrated SWAT outputs were utilized for the same purpose. Lastly, the unit pollution loads were determined by using values obtained from the literature after a comprehensive search.

3.2.1.1. Calculations performed by using water quality measurements. Measurements carried out by the Special Environmental Protection Agency were utilized to estimate the unit pollution loads. As stated previously, groundwater supply to the lake is quite low, and Lake Mogan is fed by creeks which are usually dry in summer. The hydrograph for Sukesen Creek was analyzed and it was assumed that when the streamflow rate is smaller than 0.03 m^3/s, the pollutant loads are negligible. Hence, average monthly pollution loads were calculated for the months for which the stream was not dry (>0.03 m^3/s). The unit pollution loads for the wet periods calculated at the Yavrucak monitoring station are 0.48 TN kg/ha/yr, 0.12 TP kg/ha/yr, and 15.8 TSS kg/ha/yr. The majority of Lake

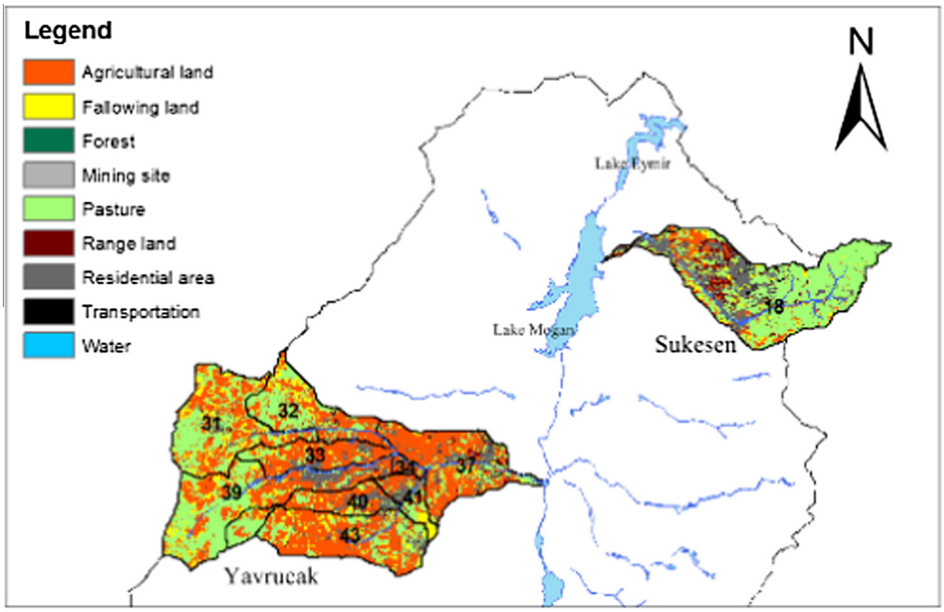

Fig. 6. Land use map of Yavrucak sub-basin (with corresponding nine sub-basins).

Table 6
Areas of land use classes in Yavrucak subbasin.

Land use class	Area (ha)	Area (%)
Water	3.0	0.0
Forest	0.2	0.0
Agricultural land	4339.1	47.0
Transportation	39.5	0.4
Residential area	1059.8	11.5
Mining site	4.8	0.1
Fallowing land	781	8.5
Pasture	2853.9	30.9
Range land	151.5	1.6
Total area	9232.7	100

Table 7
Unit pollution loads given in the literature (min.–max.) (Alp et al., 2014).

Land use class	TP (kg/ha/yr)	TN (kg/ha/yr)	TSS (kg/ha/yr)
Agriculture	0.08–3.25	2.82–41.5	4–7000
Pasture	0.01–0.25	1.2–7.1	40–80
Residential	0.19–6.23	0.6–30.85	300–2000
Industrial	1.11–1.19	3–20	80–900
Wetlands	0.001–0.2	0.5–6	–
Forest	0.007–0.83	0.69–6.26	2–9000
Recreational	0.06–2.9	2.1–79.6	800–3000

Table 8
Unit pollution loads calculated with different methods for the Yavrucak sub-basin.

	TN (kg/ha/yr)	TP (kg/ha/yr)	TSS (kg/ha/yr)
Measurement	0.48	0.12	15.8
SWAT calibrated model	0.46	0.07	2.99
Literature min.	2.0	0.1	51.0
Literature max.	29.0	2.6	4146.3

Mogan watershed shows LULC characteristics similar to the Yavrucak subbasin. Consequently, it can be assumed that unit pollution loads calculated for Yavrucak subbasin can be used to represent the entire watershed.

3.2.1.2. Calculations performed by using calibrated SWAT model outputs. The pollutant loads estimated by calibrated SWAT model at the Yavrucak monitoring station were used to estimate the unit pollution loads for flowrates higher than 0.03 m^3/s. The total pollutant loads during the three-year simulation period (2008–2010) were used to calculate the pollution load per unit area. Yearly unit pollution loads calculated using the calibrated SWAT model are 0.46 TN kg/ha/yr, 0.07 TP kg/ha/yr and 2.99 TSS kg/ha/yr.

3.2.1.3. Calculations performed using literature values. As explained previously, unit pollution loads generated from different land use classes were determined by performing a comprehensive literature search. The summary of the literature search is given in Table 7. Unit loads given in the literature show significant variations from location to location because of varying site characteristics such as climate, land use land cover, soil, crop type, irrigation method, and topography.

The unit pollutant loads given in Table 7 were multiplied with the corresponding land use areas (Table 6) in Yavrucak subbasin. The pollutant loads originating from different land uses were summed, and divided by the total subbasin area. The results of unit pollution loads calculated using these three methods are summarized in Table 8. The results show that TN and TP loads calculated at Yavrucak subbasin by using calibrated SWAT model outputs are very close to the minimum loads given in the literature. TSS loads, on the other hand, are much smaller than the literature values. The literature survey conducted in this study shows that unit loads of diffuse pollutants from agricultural land uses, even for the same crop practice category, vary by several orders of magnitude. As Novotny (2003) stated, “the most problematic of the unit load method is application to agricultural areas where commonly one of few storms is responsible for all annual loads and meteorological factors are highly variable from year to year”. In this study, pollution loads are calculated just for the wet periods, and even during the wet periods, the magnitudes of the discharge in the creeks are lower than 0.5 m^3/s and the average flowrate is just 0.1 m^3/s. Hence the calculated unit pollution loads are very close to the lower bound of the literature values even though the watershed is dominated by agricultural activities.

Table 9
Areas of land use classes for nine sub-basins used in the optimization models.

Sub-basin	Areas of land use class (ha)					Total load TN; TP (kg/yr)
	Residential	Agriculture	Fallow	Pasture	Others	
31	86.0 (5.4)	636.8 (39.8)	197.1 (12.3)	661.0 (41.3)	18.4 (1.2)	233.6; 51.5
32	64.2 (6.2)	416.2 (39.9)	94.2 (9.0)	446.5 (42.8)	22.1 (2.1)	918.2; 93.9
33	111.8 (16.1)	429.3 (61.9)	33.5 (4.8)	105.9 (15.3)	13.6 (2.0)	409.3; 90.1
34	25.0 (26.0)	59.9 (62.2)	1.1 (1.1)	6.7 (6.9)	3.6 (3.7)	30.1; 9.6
37	212.0 (15.3)	818.1 (59.1)	63.8 (4.6)	223.0 (16.1)	68.3 (4.9)	345.4; 51.2
39	222.8 (12.0)	672.0 (36.2)	154.8 (8.3)	787.4 (42.4)	19.4 (1.0)	837.8; 117.5
40	121.8 (17.1)	332.1 (46.7)	34.9 (4.9)	210.8 (29.6)	11.6 (1.6)	425.2; 86.5
41	92.5 (26.2)	105.8 (29.9)	60.0 (17.0)	75.0 (21.2)	19.9 (5.6)	184.4; 34.9
43	123.7 (8.3)	869.0 (58.2)	141.6 (9.5)	337.5 (22.6)	22.1 (1.5)	1245.2; 152.1

Percent of the total sub-basin area is given in parentheses.

Table 10
Unit loads calculated with optimization.

Unit loads (kg/ha/yr)	Residential	Agriculture	Fallow	Pasture	Others
TN	0.00	0.59	1.14	0.49	0.00
TP	0.22	0.09	0.02	0.05	0.00

3.2.2. Estimation of unit pollution loads for different land use classes using optimization

Unit loads for nitrogen and phosphorus for different land use classes are estimated using nonlinear programming. Nine sub-basins of Yavrucak sub-basin (see Fig. 6) are used to calculate unit loads for different land use classes by minimizing the error between pollution loads calculated by SWAT model and pollution loads estimated by multiplying unit loads for different land use classes with their corresponding areas (Table 9). Eq. (1) given in Section 2.4 for determining unit loads for nitrogen is modified as follows for Yavrucak sub-basin:

$$Min.\, Z = \sum_{i=1}^{9}\left[\frac{1}{A_i}\left(\left(\sum_{j=1}^{5} UNL_j A_{ij}\right) - NL_i\right)^2\right] \qquad (2)$$

where i is the index for sub-basin (i = 31, 32, 33, 34, 37, 39, 40, 41, 43) (see Fig. 6 for nine-sub-basins), j is the index for land use class (j = residential, agriculture, fallow, pasture, other), A_i is the total area of sub-basin i (ha), UNL_j is the unit nitrogen load for land use class j (kg/ha/yr), A_{ij} is the area of land use class j in sub-basin i (ha), NL_i is the total nitrogen load for sub-basin i calculated by SWAT (kg/yr).

As can be seen in Table 9, sizes of the nine sub-basins and percentages of different land use classes in these sub-basins are different. In order to balance the contribution of error in the objective function from each sub-basin, the error is weighted with the inverse of the total area of the corresponding sub-basin (see Eq. (2)). Non-negativity constraints for all decision variables (i.e., unit loads for each land use class) are implemented. To calculate unit phosphorus loads, a similar objective function for phosphorus is developed. Both optimization problems are solved using Excel Solver and the results are given in Table 10. All values are very close to each other and the major contributor of nitrogen is from fallowing land. Since agricultural activities are heavily practiced in the watershed, the unit loads developed for various land use classes are still very close to the minimum values given in the literature.

4. Conclusions

Unit pollution load method is a flexible tool that can be used by decision-makers for preliminary assessment of diffuse pollution. Even though the number of modelling and monitoring studies on diffuse pollution has substantially increased, it is still a challenging task in Turkey to incorporate diffuse pollution abatement into watershed management plans. Administrators and decision-makers are interested in correctly characterized diffuse pollution sources and implementation of effective management alternatives. Since availability of water quality data for most rivers and lakes in Turkey is limited, pollution load per unit area method becomes an option to develop management alternatives to control diffuse pollution.

In this study, unit nutrient pollution loads were calculated for the Lake Mogan watershed during the wet periods. Calculations were performed by using water quality measurements, outputs from calibrated SWAT model, and values from the literature. Unit pollution loads calculated using SWAT outputs are 0.46 kg TN/ha/yr and 0.07 kg TP/ha/yr, and they are close to the minimum values given in the literature. In addition, pollution loads for each land use class were calculated through optimization by using calibrated SWAT model outputs. Unit pollution loads calculated for agricultural lands are consistent (0.59 kg TN/ha/yr and 0.09 kg TP/ha/yr) with the values given in the literature.

If the unit pollution load method is used for the assessment of diffuse pollution, climate, topography, imperviousness, crop type, soil type, details of the agricultural practices, land use/land cover characteristics should be compared with watersheds given in the literature. In this context, if literature values are to be used in watersheds that receive limited amounts of rain and are dominated by seasonal creeks and dry agricultural practices, it is suggested that minimum unit load values from the literature and the ranges given for Lake Mogan watershed be used.

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