

A mathematical model of reservoir sediment quality prediction based on land-use and erosion processes in watershed

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Abstract. The aim of this paper is to propose a mathematical model for determining of total nitrogen (N) and phosphorus (P) content in eroded soil particles with emphasis on prediction of bottom sediment quality in reservoirs. The adsorbed nutrient concentrations are calculated using the Universal Soil Loss Equation (USLE) extended by the determination of the average soil nutrient concentration in top soils. The average annual vegetation and management factor is divided into five periods of the cropping cycle. For selected plants, the average plant nutrient uptake divided into five cropping periods is also proposed. The average nutrient concentrations in eroded soil particles in adsorbed form are modified by sediment enrichment ratio to obtain the total nutrient content in transported soil particles. The model was designed for the conditions of north-eastern Slovakia. The study was carried out in the agricultural basin of the small water reservoir Klusov.

1. Introduction

Soil erosion associated with non-point source pollution is a considerable environmental problem with respect to the off-site transport of sediment from agricultural land and nutrient-rich pollutants adsorbed to the eroded sediment into nearby waterbodies and the neighbouring environment.

Persistently high rates of water erosion affect an estimated 1,094 million hectares of land worldwide [1]. A recent new model of soil erosion by water has estimated the surface area affected in the EU-27 at 130 million ha. Almost 20 % is subjected to soil loss in excess of 10 tonnes per ha per year [2]. According to World Commission on Dams [3] it is estimated, that the world annual loss in storage capacity of the world's reservoirs due to sediment deposition is around 0.5-1%, and for individual reservoirs these values can be as high as 4-5% [4].

Together with small fraction of sediment, pollutants including nutrients are transported via surface runoff from arable land in the catchment and they are deposited in reservoirs [5]. Quantity of nutrients concentration in water reservoir sediments is regarded as the environmental pollution index and is often attributed to nonpoint source pollution from agricultural production areas.

In order to protect surface water resources and optimise their use, soil and nutrient loss must be controlled and minimised [6]. Field studies for prediction and assessment of soil erosion and sediment-associated chemical runoff are expensive, time-consuming and need to be collected over many years [7]. Nowadays, it should be rather a preference to predict of agricultural non-point source runoff of sediment and nutrients and their control using mathematical models.

The objective of this study is to propose a mathematical model for predicting the nitrogen and phosphorus concentrations in sediments from small water reservoirs and its application in agricultural watershed of the Tisovec River, Slovakia.



2. Material and methods

2.1. Study area

A mathematical model for prediction of total nitrogen (N) and phosphorus (P) content in eroded soil particles and reservoir bottom sediments has been proposed on the basis of the nutrient transport study realized in the Tisovec River catchment, located in the east of Slovakia, in Bardejov district. This catchment covers about 6.0 km² and falls in the Topla partial river basin. This catchment is affected particularly by non-point sources of pollution from agricultural production areas and no significant point source of pollution is located there. Land use within the catchment is found to be mixed type. The upstream part and middle part is an area mainly covered with forest and pastures (together 61 %), while the lower part is an arable land (21 %). The rest of the land area is for other uses.

In the narrowest part of the Tisovec River, the Klusov small water reservoir is located with its surface area of 2.2 ha and the total capacity of 72,188 m³. During 19 years of the reservoir's operation it trapped approximately 24,500 m³ of sediments delivered from the upper catchment. This situation resulted in the reduction of the total storage capacity about 33 % and thus reservoir was drained completely and desilted. Therefore the need to monitor and predict the transport of sediments and their quality is essential.

2.2. Sampling procedure

From the drained reservoir, 21 composite sediment samples were collected for determining of total N, P content in bottom sediments. Composite sediment samples were taken in nearness of dam location, especially due to deposition of fine-grained particles (fractions below 63 µm). Other sediments were sampled along the reservoir and also in various sampling depths from one locality because of detailed analysis of the stratigraphy of sediments in a reservoir. Sample S9 was taken from the Tisovec River flowing through the reservoir. Simultaneously, for determining of total N, P content in eroded soil particles, soil samples were collected from 2 units (plots 1004/1 and 2001/1) of arable land situated in the neighbourhood of the reservoir (figure 1). Within each sampling unit, at minimum 30 soil subsamples were taken from several different locations and they were mixed into one composite sample. Sampling depth was 0.30 m. In laboratory conditions, the samples were air dried at room temperature, any coarse lumps were crushed and samples were homogenized.

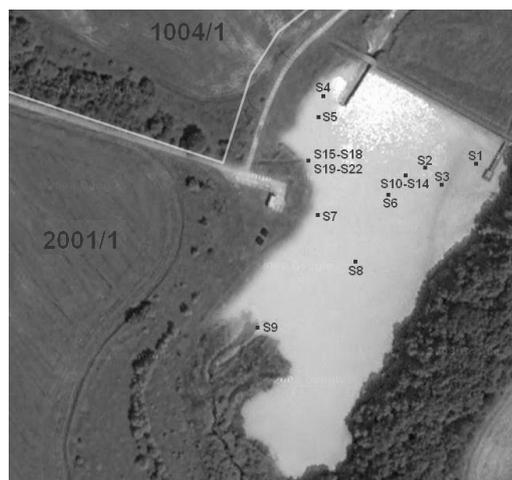


Figure 1. Location of monitored plots in the neighbourhood of reservoir and sediment sampling sites.

Adsorbed form of nutrients in sediment and soil samples were determined for total nitrogen by elemental analysis (EA) and for total phosphorus using inductively coupled plasma-atomic emission spectrometry (ICP-AES) technique.

2.3. Model design

Methodology of the proposed model (figure 2) works on the determination of total N and P concentrations in eroded soil particles in adsorbed form of followed elements. It consists of the soil

loss calculation using the Universal Soil Loss Equation (USLE) [8] and the determination of the average soil nutrient concentration in top soils.

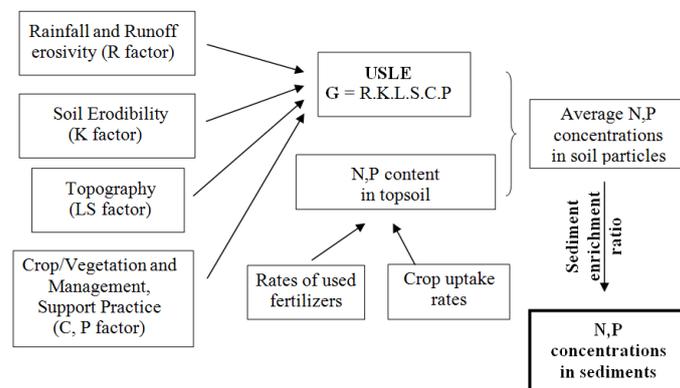


Figure 2. The scheme of suggested model for predicting the content of total nitrogen and phosphorus in reservoir bottom sediments.

The average annual vegetation and management factor in USLE equation (C factor) is specified and divided into five cropping cycle periods (seedbed preparation, establishment, development, maturing crop, stubble field). Average nutrient concentrations in top soils, divided into five cropstage periods, are computed on the basis of subtracting the nutrient input from fertiliser use (provided by the agricultural cooperative) and plant nutrient uptake (calculated according to the average yield in the studied catchment's area and the mean plant nutrient uptake values given in the [9]).

The total N, P content in transported soil particles from arable land to reservoir is calculated on the basis of the average N, P concentrations in eroded soil particles in adsorbed form detached through water erosion modified by sediment enrichment ratio [10] using this proposed equation (1):

$$C_x = \frac{\sum_{i=1}^5 X_i \cdot G_i}{G_{r,i}} \cdot SER = \frac{\sum_{i=1}^5 X_i \cdot G_i}{G_{r,i}} \cdot e^{2 \cdot 0.21 \ln(G_{r,i} \cdot 1000)} \quad (1)$$

where C_x is an average annual concentration of total N, P in transported soil particles from monitored plot in kg N,P ha⁻¹ or mg N,P kg soil⁻¹; X_i is residual concentration of total N, P in soil in i -period in kg N,P ha⁻¹ determined as the subtraction of the total nutrient concentration in soil and plant available nutrients in soil; G_i is soil loss in individual cropping periods in t ha⁻¹ and $G_{r,i}$ means an average soil loss in i -year from monitored plot in t ha⁻¹ year⁻¹. The total concentrations of N, P in reservoir bottom sediments are then computed as a weighted mean of the calculated average annual concentration of total N, P in transported soil particles from monitored plots surrounding the reservoir.

3. Results and discussion

The total nutrient concentrations in eroded soil particles in dissolved form of followed elements weren't considered in this proposed model, because the portion of dissolved phase represented 0.22 – 0.43 % of total N and 0.45 – 0.86 % of total P in the soil sample.

Calculations of total N and P concentrations in eroded soil particles in adsorbed form were realized for two units (plots 1004/1 and 2001/1) of arable land situated in the neighbourhood of the Klusov reservoir. Calculated total N and P concentrations in bottom sediments were determined during the 10-years crop rotation system in the Klusov small water reservoir.

The average annual soil loss ranged from 1.9 to 17.7 t ha⁻¹ year⁻¹ for plot 1004/1 and from 5.34 to 27.7 t ha⁻¹ year⁻¹ for plot 2001/1 depending on the crop. Long term average annual soil loss is 8.3/14.3 t ha⁻¹ year⁻¹ for plots 1004/1; 2001/1 depending on the crop, plot length and slope gradient.

The most widely used fertilisers in the watershed were NPK fertilisers (8.5% or 15% N), ammonium nitrate (27% N). For crops common grown in Slovakian conditions, an average plant nutrient uptake divided into five cropstage periods was devised (table 1).

Table 1. Proposed average plant nutrient uptake divided into five cropping periods.

Crop	(kg ha ⁻¹)	Cropping period					\sum_1^5
		1.	2.	3.	4.	5.	
spring barley	N	0.00	15.90	17.75	20.00	0.00	53.65
	P	0.00	2.05	2.50	3.70	0.00	8.25
	K	0.00	18.65	21.80	19.55	0.00	60.00
winter wheat, triticale,	N	0.00	0.00	19.10	71.35	0.00	90.45
	P	0.00	0.00	1.25	10.75	0.00	12.00
	K	0.00	0.00	9.55	67.50	0.00	77.05
winter rye	N	0.00	9.90	68.90	30.00	0.00	108.80
	P	0.00	1.40	15.90	5.00	0.00	22.30
	K	0.00	6.20	88.10	7.70	0.00	102.00
winter oilseed rape	N	0.00	18.30	17.70	26.30	0.00	62.30
	P	0.00	1.90	1.80	2.60	0.00	6.30
	K	0.00	8.50	8.20	12.10	0.00	28.80
pea	N	0.00	18.27	17.66	53.00	0.00	88.93
	P	0.00	2.61	2.52	7.58	0.00	12.71
	K	0.00	23.49	22.71	68.15	0.00	114.35
potatoes	N	0.00	16.35	16.89	50.18	0.00	83.42
	P	0.00	2.18	2.19	6.75	0.00	11.12
	K	0.00	13.62	13.67	42.22	0.00	69.51

The average nutrient concentrations in eroded soil particles in adsorbed form were modified by sediment enrichment ratio to obtain the total nutrient content in transported soil particles. Sediment enrichment ratios *SER* computed based on the average soil loss in *i*-year from monitored plots were in range from 0.97 to 1.63.

The total concentrations of N, P in reservoir sediments (table 2) were then computed as a weighted mean of the calculated average annual concentration of total N, P in transported soil particles from monitored plots surrounding the reservoir.

Table 2. Calculated concentrations of total N, P (%) in reservoir sediments.

Year	N (%)	P (%)	K (%)
1.	0.188	0.067	1.956
2.	0.225	0.078	2.307
3.	0.188	0.066	1.944
4.	0.225	0.082	2.387
5.	0.203	0.072	2.131
6.	0.193	0.068	2.032
7.	0.189	0.065	1.954
8.	0.236	0.083	2.469
9.	0.199	0.069	2.071
10.	0.202	0.070	2.096

Calculated concentrations of total N, P in reservoir sediments correspond to the measured nitrogen (0.16 to 0.26 %) and phosphorus (0.05 to 0.11 %) concentrations in collected sediments.

4. Conclusion

Sediment, soil particles that end up in the water, reduces the basin's accumulation capacity. Sediment runoff can also pick up and transport additional pollutants such as nutrients that threaten the good ecological status of waterways and water basins. In order to protect surface water resources and optimise their use, soil and nutrient loss must be controlled and minimised. In this way, mathematical models provide a useful tool for assessing and forecasting the nutrient content in reservoir bottom

sediments. This paper summarizes the results of the study aimed at the proposal of a mathematical model to predict the nitrogen and phosphorus concentrations in eroded soil particles and reservoir bottom sediments. The results showed that calculated concentrations of total nitrogen and phosphorus in reservoir sediments correspond to the measured N, P concentrations in collected sediments.

Acknowledgments

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