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Water Quality Modeling and Evaluation of Nutrient Control Strategies Using QUAL2K in the Small Rivers

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A R T I C L E I N F O

A B S T R A C T

Background: Qual2k is a stream water quality model and was used to evaluate the water quality of the Kine-Vars River and assess the response of the river to nutrient management strategies.

Methods: For that purpose, 7 sample stations were selected and surface water samples were collected in the winter and summer of 2012 and were analyzed for temperature, dissolved oxygen, biological oxygen demand, ammonia–nitrogen, nitrate–nitrogen, organic nitrogen, organic phosphorus, and inorganic phosphorus.

Results: Results showed that the Kine-Vars River is saturated with N and P and is classified as eutrophic. The simulated data showed that the total nitrogen and total phosphorus loads of the studied river need to be reduced by 76% and 93%, respectively, to reach water quality objectives.

Conclusion: Application of nutrient control strategies can reduce the nutrient loads significantly but is not sufficient to change the river classification from eutrophic to oligotrophic in a short time; thus, additional nutrient control measures are necessary.

1. Introduction

Water is a vital resource for life, and its quality is one of the most important factors for human health. Because of decreasing water quality due to the disposal of human waste into water bodies, most of the countries around the world are forced to develop remediation methods in order to conserve water.

rivers depends on land use in the basin and chemical composition of runoff [1].

Industrialization and increasing populations are accompanied by the production of effluents and wastes. Most rivers and their tributaries in Iran, such as the Zayande Roud and the Karoon, are reported to be polluted because of an inflow of liquid and solid wastes [2, 3].

In water quality management programs, it is essential to evaluate the human impacts on surface and ground water quality.

Agricultural, industrial, and municipal wastes are discharged into rivers, and therefore the concentration of nutrients and organic materials can be predicted. An increase in nutrients and other contaminants accelerates the eutrophication process and depletes the oxygen of the rivers.

The installation of dams on rivers is the best way to store river water for irrigation, drinking, and industrial usages. In Iran, there are 692 operational dams and 670 dams in construction and study phases. In recent years, the construction of dams has accelerated because of an increase in population and development plans in the agricultural and industrial industries. Hundreds of industries, villages, and cities are located beside these rivers and contribute to the discharge of solid and liquid wastes into the rivers. There are many models for the assessment of water quality in rivers.

Mathematical models are the best method for studying the waste stream effects on water bodies. Some of them are presented as equations for the prediction of one or several water quality parameters [e.g., the prediction of dissolved oxygen through mathematical modeling as reported by Naik, V. K. and Manjapp, S. [4]. In recent years, most mathematical models have been presented through designated software. Some of these software programs are very complex and need data, which are scarce for small rivers. One of the simpler models for the modeling of water quality in rivers is Qual2k. This model is based on the relationship between the river, pollutant loads, sediments, algae, and the atmosphere [5]. Qual2k is functional even when some monitoring data from the river is insufficient for other, more complex models [6].

Qual2k has been applied for the simulation of many rivers, including the Certima River in Portugal, the Bagmati River in Nepal, the Dali River in Taiwan, the Neckar River in Germany, and many others [7,8].

The aim of this study was to apply the Qual2k model to the simulation of a small and short river with limited data and to assess the effects of pollution control methods.

One of the most important parameters in the simulation of river water quality is nonpoint source pollution. Agricultural nonpoint source pollution is very difficult to assess [9]. The contribution of nonpoint source nutrient pollution in areas with extensive agricultural land uses accounts for more than 70% of the total pollution, and phosphorus as a nonpoint source from agricultural activities plays a significant role in the restoration process. In most of the literature, authors used the emission factors for the calculation of agricultural runoff loads based on land use without considering the decay process of nutrients in the soil [10,11].

Most studies conducted using the Qual2k model are applied to the modeling of large and long rivers. In this study, the estimated concentrations of nutrients from runoff by Benaman (1996) were used, and after the calculation of the decay rates of nutrients, the pollution load of runoff was determined and was used in the Qual2k model [12].

Study area

The Kine-Vars River originates in the southern mountains in the vicinity of the city of Zanjan in northwestern Iran. It begins in the Sendan, Salar Daghi, and Rostam

mountains and flows down to a valley, finally reaching the Abhar Roud River with an average daily flow of 71000 m³/d.

The Kine-Vars dam was built at a distance of 20 km from the origin of the Kine-Vars River in 2009. The lake formed by this dam will be the main drinking water source for the cities of Abhar and Khoramdareh with a total population of about 130000, the main irrigation source for 1600 ha of agricultural lands, and will also provide water for industrial activities.

The Kine-Vars basin has an area of approximately 372 km² and an interior Mediterranean climate. The main occupations of the active population of the villages in the basin are related to agriculture. There are no sewage systems or wastewater treatment facilities in the region, and septic tanks in the rural areas are directly or indirectly discharged into the river or into shallow wells. Uncontrolled and unmanaged usage of chemical fertilizers and pesticides in the agricultural industry produces the main nonpoint source of pollution in the basin.

There are 20 villages in the basin beside the river with a total population of about 6000 (Fig. 1). There is no factory or industrial activity in the study area except a mine whose soil is transported from the basin for silicon extraction. A length of 20 km from the headwater to the Kine-Vars dam was selected for this study.

In order to collect water quality data, 7 stations (S1 to S7) were selected. The locations of the stations are shown in Figure 1. S1 is located at the headwater; S3 and S5 represent the two main tributaries (point sources); and S2, S4, S6, and S7 were used as control points for validation of the model.
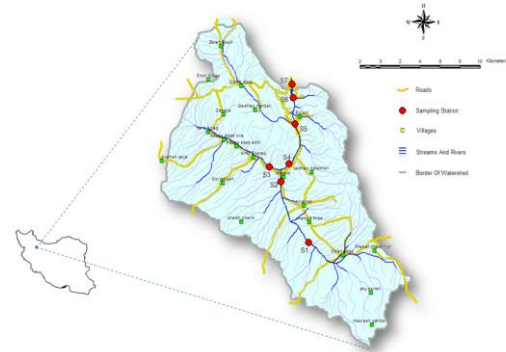
Fig. 1: Study area: The Kine – Vars River basin, Villages and monitoring stations along the river. Monitoring sites and data.

Sampling was performed in the winter and summer of 2012 as wet and dry seasons, respectively. The following water quality parameters were measured: water temperature, flow, velocity, depth, dissolved oxygen, biological oxygen demand (BOD), ammonia–nitrogen (NH_3–N), nitrate–nitrogen, organic nitrogen (org. N), organic phosphorus (org. P), and inorganic phosphorus (Inorg. P).

All of the samples were collected, preserved, and analyzed according to the methods described in standard methods for water and wastewater examination [13].

Some parameters such as temperature and DO were measured using portable sensors in the field. In each season, the mentioned parameters were measured once a month and the average values of every 3 months are presented in Table 1.

Qual2k model

Qual2k is a one dimensional model for the simulation of river and stream water quality, which was developed by the USEPA [14]. The model divides a river into several reaches, and tributaries are not modeled

explicitly, but can be represented as point sources. A steady-state flow balance and a general mass balance for a constituent in an element are written as follows:

$$Q_i = Q_{i-1} + Q_{in,i} - Q_{ab,i}$$

$$\frac{dc_i}{dt} = \frac{Q_{i-1}}{V_i}c_{i-1} - \frac{Q_i}{V_i}c_i - \frac{Q_{out,i}}{V_i}c_i + \frac{E'_{i-1}}{V_i}(c_{i-1} - c_i) + \frac{E'_i}{V_i}(c_{i+1} - c_i) + \frac{W_i}{V_i} + S_i$$

where Q_i = outflow from reach i into the downstream reach $i + 1$ [m^3/d], Q_{i-1} = inflow from the upstream reach $i - 1$ [m^3/d], $Q_{in,i}$ is the total inflow into the reach from point and nonpoint sources [m^3/d], $Q_{ab,i}$ is the total outflow from the reach due to point and nonpoint abstractions [m^3/d], W_i = the external loading of the constituent to element i [g/d or mg/d], and S_i = sources and sinks of the constituent due to reactions and mass transfer mechanisms [g/m^3/d or mg/m^3/d] [15].

Table 1: The water quality parameters of the Kine – Vars River.

| Parameter | Wet season | | | | | | | Dry Season | | | | | | |
| | Monitoring station | | | | | | | Monitoring station | | | | | | |
	S1	S2	S3	S4	S5	S6	S7	S1	S2	S3	S4	S5	S6	S7
DO	4.5	4.7	4.8	7	5.4	6	7	4.2	7.5	4	7.5	5.1	6.9	7.4
CBODf	4.5	5	8.6	5	5.1	6.7	7	5	5	10	5.3	5.7	7	6.8
Org. N	0.74	1.6	1.9	1.5	0.11	1.4	1.3	0.85	1.7	2	1.6	0.12	1.5	1.3
NH$_4$	0.021	0.58	0.25	0.69	0.045	0.78	0.88	0.02	0.66	0.3	0.77	0.05	0.82	0.92
NO$_3$	0.2	1.8	1.7	1.5	0.7	1.9	2	0.18	1.2	1.2	1.3	0.5	1.5	1.7
Org. P	0.018	0.047	0.017	0.035	0.019	0.023	0.022	0.023	0.054	0.02	0.049	0.022	0.025	0.035
Inorg. P	0.068	0.298	0.48	0.42	0.07	0.4	0.3	0.075	0.375	0.514	0.41	0.08	0.471	0.5

In this study, the river was divided into 4 reaches, and the model assumes that the physical, chemical, and biological properties of water are constant along each reach. Each reach was subdivided into 2000 m intervals for solving the differential equations of the model. Many parameters such as DO, BOD, pH, TN, and TP can be simulated by this model.

Input data

The input data for the Qual2k model were meteorological, hydraulic, and water quality data as well as point and nonpoint source pollution loads. The metrological data were Obtained from the meteorology administration of the city of Zanjan.

The water quality and hydraulic parameters were measured after sampling in monitoring stations. Some hydraulic and hydrologic parameters were obtained from the reports of the Kine-Vars Dam construction. In order to calculate the pollution loads of human effluent as well as animals and runoff pollution, per capita pollution load and runoff estimated concentration values were used. The coefficients used and the basic data for the calculation of pollution loads are presented in Table 2 [16]. The input loads from tributaries into the main river were considered as point sources and were

determined by the measuring of water quality parameters in monitoring stations at these points.

Table 2: The basic data for the calculation of the pollution loads (Naranjo, 1997).

Parameter	Value
Population	6000
Basin area (Km^2)	372
Runoff estimated mean concentration (mg/l)	TN=1.58 TP=0.36 CBOD=4
Runoff coefficient	0.06
Human per capita loads (Kg/cap. y)	TN=4 TP=0.5 CBOD=13
Livestock pollution loads(g/animal.d)	TN=210 TP=27

Nonpoint Source Concentrations

In this study, the pollution load of runoff was determined on the basis of estimated mean nutrient concentrations (EMCs) [12]. According to this model, the runoff pollution load is achieved as follows:

Pollution load = runoff coefficient × precipitation × EMC,

where EMC = Runoff estimated mean concentration. The EMC values of different land uses were determined by Benaman et al. (1996) and those used in this study are presented in Table 3.

A runoff coefficient of 0.06 was obtained using the SCS method.

N, P, and BOD decay through biogeochemical processes in the soil [16], so the final loads of pollutants were determined using the following formulas: $N = L_N \exp(-K_N d)$; $P = L_P \exp(-K_P d)$; $BOD = L_{BOD} \exp(-K_{BOD} d)$; where d = the mean distance between the location of pollution production and the river (km; the length of pollution transportation), k = the specific rate of decay

of pollutants ($\frac{1}{km}$) = 0.16, 0.09, and 0.26 for N, P, and BOD, respectively.

In this study, the length of transportation of pollution was determined on the basis of an equivalent rectangle of basin area. In order to evaluate the control measures for nutrient reduction in the river, two strategies were defined. In the first scenario, the effects of collection and treatment of human effluents (domestic wastewater) were evaluated, and in the second scenario, the simultaneous effects of wastewater treatment plant discharge (first scenario) and the control of runoff pollution via a combination of detention ponds and filter buffer strips were considered [17].

The simulation of the river was performed with the same calibrated parameters and different conditions for each defined scenario.

Table 3: The runoff estimated concentration values (mg/l).

Land use	TN	TP	BOD
Agricultural	1.56	0.36	4
Open/Pasture	1.51	0.12	6

3. Results
3.1. Model calibration and validation

In order to find the values for the model parameters that best fit the system to be modeled, the model should be calibrated [18]. In this study, the auto calibration mode was used for the calibration of the model. The measured data of stations S1, S2, and S4 in winter 2012 were used for the calibration of the model. The input data were temperature, pH, conductivity, DO, BOD5, NH4, NO2, org. N, org. P, inorg. P, average daily flow, depth, and flow velocity. The auto calibration parameters and the calibrated values are shown in Table 4.

In order to evaluate the ability of the calibrated model to predict the river water quality, the results of the simulation by the calibrated model were compared with measured data of 4 control stations of summer 2012. The correlation coefficients between the simulated and field monitored data (R) were calculated using the mean values of water quality parameters of 4 control stations. The dry season data were selected because the concentrations of pollutants in the dry seasons are higher than in the wet seasons. The results are presented in Fig. 2 and Table 5.

The calibrated results of the model were in accordance with the monitoring results. Pierson correlation coefficients were higher than 0.9 in the cases of DO, CBOD, and TP,

and for TN was 0.891. The calibrated parameters from the winter season confirmed the model with water quality data from the summer season. Dissolved oxygen is one of the most important water quality parameters in surface waters, and it influences the flora and fauna of ecosystems [19]. The results show that the DO concentration does not meet the minimum DO standard of 4 mg/l in the studied length of the river. The minimum DO concentration at the headwater is 4.2 mg/l, and beyond that the DO concentration increases for further 8.7 km, where the DO curve shows a sag due to the discharging of tributaries with low DO concentrations upstream of this point. The CBOD

Table 4: The calibrated parameters for simulating the of the Kine – Vars River water quality.

Parameters and rates	Value	Unit
Carbon	40	gC
Nitrogen	7.2	gN
Phosphorus	1	gP
ISS settling velocity	0.1	m/d
Oxygen reaeration model	Tsivoglou-Neal	
Fast CBOD:		
Oxidation rate	1.5	1/d
Organic N hydrolysis	1	1/d
Organic N settling velocity	0.72	m/d
Ammonium nitrification rate	5	1/d
Nitrat denitrification rate	2	1/d
Sed Denitrification transfer coeff.	1	m/d
Organic P hydrolysis	0.736	1/d
Organic P settling velocity	0.032	m/d
Inorganic P settling velocity	0.5	m/d
Sed P oxygen attenuation half sat constant	2	mg O_2/l
Bottom algae		
Growth model	Zero order	
Max growth model	90	1/d
First-order model carrying capacity	72000	mgA/m^2
Respiration rate	0.01	1/d
Extraction rate	0.24	1/d
Death rate	0.4	1/d

Concentration at this point is 7.06, which is the highest CBOD value.

The results of the mean concentrations

of TN and TP at the end of the studied length of the river are 2.9 and 0.3 mg/l, respectively.

These values are very important and should be considered because the end of the studied river length is the entrance point of the river into the dam lake. These nutrients are the main agents of eutrophication of the lake, which supplies drinking water to the cities of Abhar and Koramdareh.

In order to evaluate the trophic condition of the river, the criterion of Dodds et al. (1998) was used [20].

The results of simulation of the Qual2k model show that the concentrations of TN and TP along the river ranged from 1.05 to 2.9 mg/l and 0.098 to 0.3 mg/l, respectively, which is higher than the mentioned criterion. The monitoring data for the evaluation of the calibrated model showed similar results, therefore the river is eutrophic. The results are shown in Table 6. According to the simulated data the TN and TP pollution loads of the studied river need to be reduced by 76% and 93%, respectively, to satisfy the water quality guidelines of the oligotrophic–mesotrophic boundary.

The capacity of the river to healthily accept pollution (self-purification) was determined using the following formula [21]:
$$W = Q\,(C_s - C) + k\,C_s\,(L/U)\,Q,$$
Where W = Self–purification capacity kg/d; Q = Flow (m^3/d); C$_s$ = Standard concentration of pollutant (kg/m^3); C = Concentration of pollutant (kg/m^3); L = Length of the river (m); U = Water velocity (m/day); K = Specific degradation rate (1/d).

The values of W for BOD were determined in 2 sections of the river. Segment 1, measured from the end of the studied length (0.00) to 10 km (between stations of 3 and 7), and segment 2, measured from 10 km to 19 km (between stations of 1 and 3), were

considered to be the two main sections of the river. The results are shown in Table 7.

Segments 1 and 2 have the capacity of 50 and 230 kg/day for acceptance of BOD, respectively, but the river is still in critical condition because of high concentrations of N and P. This means that the self-purification capacity could not represent the condition of the river without considering the role of N and P. Because of the above reasons, control strategies for the water quality of the Kine-Vars River should be evaluated.

3.2. Control strategies

Two scenarios were designed for the control of pollution in the river. The first was the collection and treatment of human effluent in the villages of the basin via building a wastewater treatment plant (WTP). The second strategy was building the wastewater treatment plant plus using runoff pollution control using detention ponds and filter buffer strips [22].

It was assumed that the minimum efficiencies of the WTP and runoff pollution control measures for the removal of BOD, TN, and TP would be 90 and 50 percent, respectively.

This efficiency can be achieved using processes such as biological nitrification–denitrification and oxic–anoxic systems for TP and TN removal [23, 25].

In order to evaluate the response of the Kine-Vars River to the N and P reduction strategies, the calibrated model was run with new data, and the control nutrients were simulated [18]. As shown in Figure 3, a wastewater treatment plant can reduce the nutrient concentrations in the river but it is not sufficient to meet certain water quality criteria. The results of the modeling of

scenario 2 showed a significant reduction of
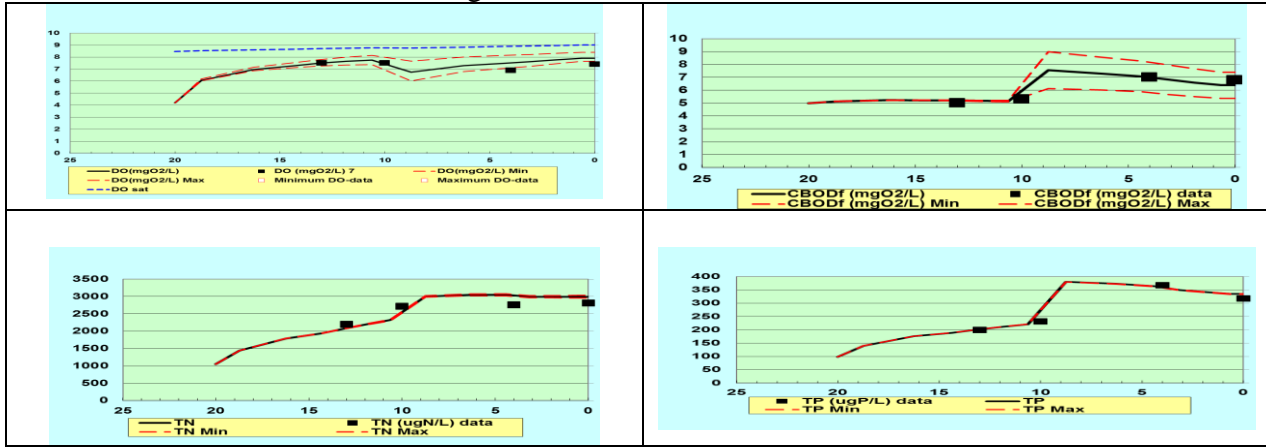nutrient loads, with the TN reaching close

Fig. 2: The results of water quality simulation by calibrated model compared with measured data of 4 control stations.

Table 7: The self- Purification capacity of the Kine-Vars River.

Segment	U (m/day)	L (m)	C (kg/ m³)	C s (kg/m³)	K (l/d)	W (kg/d)
1	50112	10000	0.00516	0.005	1.5	50
2	54432	10000	0.00687	0.005	1.5	230

Table 5: Comparison of monitored and modeled values of the water quality parameters of the Kine – Vars River.

	Stations	Monitored Value(mg/l)	Modeled Value(mg/l)	correlation
DO	S2	7.5	7.46	R=0.975
	S4	7.5	7.72	P=0.042
	S6	6.9	7.46	
	S7	7.8	7.88	
CBOD	S2	5	5.21	R=0.966
	S4	5.3	5.18	P=0.034
	S6	7	7.08	
	S7	6.8	6.39	
TN	S2	2.075	3.57	R=0.891
	S4	2.327	3.82	P=0.109
	S6	3.049	3.9	
	S7	2.993	3.95	
TP	S2	0.200	0.415	R=0.982
	S4	0.221	0.443	P=0.018
	S6	0.363	0.515	
	S7	0.334	0.515	

Table 6: Suggested boundaries for trophic classification of streams and the results of the present study.

Variable	Oligotrophic– Mesotrophic boundary	Mesotrophic– eutrophic boundary	Simulated data	Monitoring data
TN (mg/l)	0.7	1.5	1.05- 3	2.1 – 2.8
TP (mg/l)	0.025	0.075	0.098- 0.38	0.19 – 0.31

to 1.6 mg/l, which is the boundary level for the mesotrophic and eutrophic class. It is clear that even with the above mentioned strategies, more control measures should be implemented in order to meet the water quality objectives.

The main reason for this is that the Kine-Vars River basin is enriched with nutrients and the intrinsic concentrations of TN and TP are very high.

Uncontrolled usage of fertilizers is the main source of nutrients, and the discharge of solid waste into the river by villagers and tourists, the accumulation of N and P in the soil of the basin, and some activities such as washing of cattle in this small river are considerable sources of pollution but have not been taken into account in this study
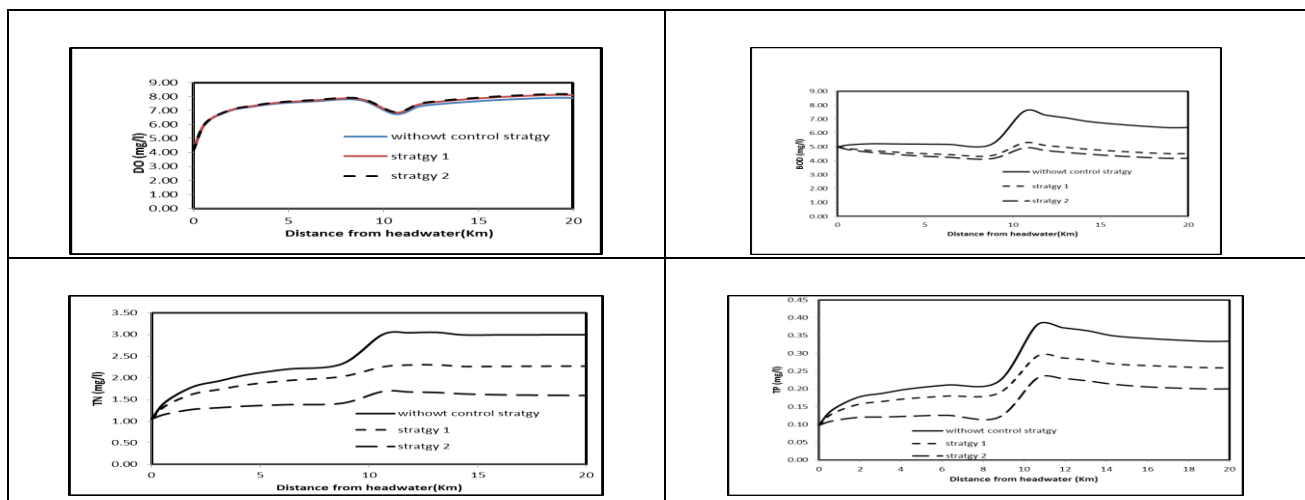

Fig. 3: The simulation curves of water quality parameters with and without the control strategies.

4. Discussion and conclusion

The simulated and monitored results showed that the Kine-Vars River is saturated with N and P. At the present time, the Kine-Vars River is classified as eutrophic.

The application of control strategies for the reduction of N and P are not sufficient to change the river classification to oligotrophic. In spite of the above simulated control measures, some activities are necessary to control and reduce the pollution loads such as follows:

1- Education of simple water quality measures to the inhabitants of the basin.

2- Performance of best management strategies on the basis of conservation of the river for usage of fertilizers.

3- Application of other nonpoint source control measures with higher than 50% efficiencies such as grass barriers along the river.

4- Control of the discharge of solid waste into the river.

The simulated data by the Qual2k model were valid so the model can be used for water quality modeling of small rivers and for assessing different scenarios for pollution control.

Qual2k is a simple model and is useful for small basins for which some data are scarce, and the applied method in this study is a simple and valid tool for water quality management and decision-making.

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