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Assessment of Basin-Scaled Nutrient Load Management Strategies; Minab Dam Watershed

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Abstract

Eutrophication is a serious water quality issue that occurs due to the excess nutrient loads entering the water bodies. Esteghlal Dam is the source of supplying 50% of the drinking water of Bandar Abbas, which has been affected by algal blooms due to the excess nutrient loads from the Minab basin. The purpose of this study is to identify Critical Source Areas (CSAs) and study and prioritize management scenarios to reduce pollution load to the reservoir. In this study, we used an integrated quantitative and qualitative simulation approach at the basin scale. We applied the SWAT model as a comprehensive process-oriented model to simulate the entire watershed. After identifying CSAs, we assessed the impact of each management scenario on reducing the nutrients. Finally, based on the nutrient load reduction and the investment and operating costs of each scenario, we select appropriate solutions using a multi-criteria decision-making approach. The results showed that agricultural and pastures (livestock) land uses in Jaghin and Minab sub-basins are CSAs. In addition, Filter Strip with a width of at least 10 meters and Fertilizer Reduction on Farms were recognized as the most effective strategies.

Keywords: Water Quality Management, Comprehensive Watershed Simulation, Critical Sources Areas, Best Management Practices (BMPs), Esteghlal Dam Watershed

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Introduction

Recently, many water quality issues such as eutrophication have caused serious problems in supplying drinking water. This phenomenon occurs due to the excess nutrient loads entering the water bodies and has a wide range of adverse effects including a severe drop in dissolved oxygen, improper taste and odor, toxicity, and mortality of aquatic animals. In a watershed, there are some areas with a particular type of soil, land use, vegetation, and topography that are at a greater risk for nutrient production and higher sediment loads, called Critical Source Areas (CSAs). Comprehensive modeling of the watershed system helps identify and quantify nutrient loads in CSAs which allows for recognizing and prioritizing effective nutrient reduction plans such as farm and watershed management strategies. Esteghlal Dam is the source of supplying 50% of the drinking water of Bandar Abbas, which has been affected by algal blooms due to the excess nutrient loads from the Minab basin. The purpose of this study is to identify Critical Source Areas (CSAs) and study and prioritize management scenarios to reduce the pollution load into the reservoir.

Materials and Methods

Study area

Minab basin is located at latitude 26°57'00" to 28°24'00" N and longitude 56°49'00" and 57°53'00" E. About 29% of the watershed has a height between 0 to 500 meters, 52% between 500 to 1000 meters, 10% between 1000-1500 meters and the rest is more than 1500 meters.

Minab River consists of two main tributaries, Rudan and Jaghin. These two rivers are joined near Brentine and form the Minab River. The Minab River flows southwesterly to the Minab Dam, and after the dam, it changes direction to the west and enters the Oman Sea.

The reservoir of Esteghlal Dam has suffered from algal blooms due to excessive nutrient load from the watershed, including sewage of upstream villages, animal waste, agricultural wastewater, waste leachate, erosion, etc. Consequently, nowadays, taste and odor are considered as one of the main challenges of this dam.

Simulation Model

The Soil & Water Assessment Tool (SWAT) is a basin-scale and semi-distributed model developed by Arnold et al. in 1998. This model enables to simulate the impact of different management practices on water, sediment, and agricultural pollutants in a watershed with diverse types of soils and land use. The main inputs to the model are topography, soil characteristics, land use, vegetation type, climate variables, and land management practices. In the SWAT, the basin is divided into several sub-basins and each sub-basin is divided into a large number of Hydrologic Response Units (HRUs) based on topography, land use, and soil type. Each HRU represents an area that contains a unique combination of land use, soil type, and slope class. Daily runoff is estimated by the SCS curve number method. Erosion and sedimentation in each HRU are calculated based on the Modified Universal Soil Loss Equation (MUSLE) and the Bagnold Modified Sediment Transfer Equation. In order to simulate nutrient transfer in SWAT, various factors such as mineralization, decomposition, nitrogen and phosphorus uptake, erosion, and sedimentation rate should be taken into account. Accordingly, the entire basin of Esteghlal Dam was divided into 29 sub-basins and 1350 HRUs.

In this study, we used the monthly observed data in 2018. Then, the parameters related to each of the main components of the model including plant (Dat), soil (Sol), groundwater (Gw), management (Mgt), and river (Rte) were introduced to the model. The important point is about how to define various agriculture and irrigation planning and management practices to the model to reduce the difference between the modeling conditions of watershed hydrological processes and the real conditions. To do so, land uses are broken down into smaller sections to first apply the cultivation pattern in each sub-basins and secondly to manually assign Crop calendar data as well as agricultural operations (such as fertilization, etc.) to relevant HRUs. The pollution load of residential areas was also estimated by multiplying the number of individuals and the approximate per capita nutrient load production.

Sensitivity analysis

Sensitivity analysis of model parameters is of paramount significance in investigating the extent of their impact on model outputs. There are varied methods to analyze the sensitivity and uncertainty of the SWAT model. In this study, we used the SUFI-2 algorithm to recognize the parameters with the greatest impact on the watershed outflow (inflow to the reservoir) and water quality. Analyzes showed that the curve number (CN2) has the greatest effect on the outflow of the basin. Among parameters affecting nutrient loads, algae mass percentage in form of phosphorus (AI2) and parameters related to the nitrogen cycle, such as (BC3) and (BC2) have the highest sensitivity.

Model calibration

In this study, simulations were performed for 29 years from 1990 to 2018. Calibration and validation of nutrient concentrations require accurate estimation of the flow. Thus, the model was calibrated and validated in a multi-step process. First, precipitation and evaporation at the basin level as well as actual yield and evapotranspiration were calibrated. Then the parameters affecting the discharge are calibrated. Finally, nutrient load parameters are changed to achieve the proper accuracy.

Critical Source Areas

To identify and compare CSAs, the simulated nutrient loads and runoff were analyzed at the level of each HRUs. Then, the average annual load per unit area of each HRU, total nitrogen (TN), and total phosphorus (TP) were estimated by calculating the weighted average in all land uses and considering cultivation patterns. By dividing these values by the total load of the basin, we find the percentage share of each land uses in producing TN and TP. Based on this, land uses that have more than 20% contribution to nutrient production and runoff are selected as CSAs.

Long-term Strategies to control nutrient loads

1-Management strategies on the farm

Considering the agricultural land use as a CSA in terms of total nitrogen load (TN), it seems necessary to see how declining fertilizer use can affect TN control. Therefore, we supposed that the use of nitrogen and phosphate fertilizers is simultaneously reduced by 25% and 50%. Furthermore, animal manure is decreased by 25% and 50%, respectively.

2-Residential wastewater management

Residential areas in the Minab watershed are an important factor in the transfer of nutrients into the river. In this strategy, due to the operation of the Rudan wastewater treatment plant and the implementation of the first phase of the Minab wastewater treatment plant, it is assumed that pollution from the residential areas of Ziarat Ali, Nodej, Manojan, and Deh Barez has been reduced by 30 to 60 percent.

3-Watershed management strategies (Filter Strip)

Filter Strip is used to remove urban and agricultural contaminants before they reach the water body. A Filter Strip is a plant-covered strip that filters contaminants by reducing the flow rate and the sedimentation. Based on the watershed slope of 5 to 20% in critical sub-basins, the filter is defined with a width of 12 meters.

4-Terracing CSAs (Rangeland)

Terracing is a strategy to protect water and soil. This strategy is implemented in lands with a slope of 8 to 12 percent. The appropriate distance between the terraces is 120 to 180 cm. the strategy is applied in the SWAT by changing the average slope of the basin, CN parameter (runoff curve number), and USLEP parameter to reduce erosion.

Results and Discussion

The calibration and validation process showed that the developed model has sound reliability to simulate the discharge and water quality at the basin level. The simulation results show that the annual

inflow to the reservoir has decreased in recent years causing an increase in the concentration of nutrient loads. The highest flow is recorded at 25 m3/s in 1993. The long-term simulation average is 5.8 m3/s which is slightly higher than the observed of 5.65 m3/s. Also, in the short term (10-year interval) these values are 3.4 and 3.3 m3/s, respectively. The simulated nutrient concentrations showed that total nitrogen (TN) has been on the rise, from about 8 mg/L in 2002 to more than 19 mg/L in 2018. The concentration of total phosphorus (TP) has also increased to about 3 mg/L. The ratio of TP to TN is about 15%, while standards suggest the number is less than 10%. To determine the CSAs, we used two combined indices with different weights. The first index CI(1) considers equal weights of 0.33 for sediment load, TN, and TP. The second index CI(2) takes 0.2 for sediment load, 0.4 for TN, and 0.4 for TP into account, respectively. These weights were calculated using the entropy method.
Crops have the highest share in total nitrogen production compared to other land uses. Animal husbandry also has the greatest share in sediment production and total phosphorus. Based on the first index, traditional animal husbandry is the most critical source in terms of pollution and sediment production. According to the results, Jaghin and Minab sub-basins have the highest potential for nutrient production and erosion.
After examining the effect of each management strategy using the simulation model, there is a need to compare their effectiveness by scoring, weighing, and ranking them. According to the results, the highest score for the reduction of organic nitrogen was for Terracing and the lowest score was given to the reduction of traditional livestock. The highest priority for reducing total nitrogen is to reduce chemical and animal fertilizers on the farm. Also, the highest priority in reducing phosphorus is the implementation of Filter Strip in CSAs. To determine the priority of management strategies, we utilized the Multi-Criteria Decision-Making approach based on the experts’ opinions and the results of the effectiveness of strategies as well as their implementation costs.
Results showed that implementation of Filter Strip (with a minimum width of 10 meters) in Critical Source Areas has the highest priority in reducing nutrient loads and controlling Eutrophication. Then, terracing farmland on steep slopes was ranked as a second priority and strategy to control erosion and nutrient load production.

Conclusions

In this study, we used an integrated quantitative and qualitative simulation approach at the basin scale. We applied the SWAT model as a comprehensive process-oriented model to simulate the entire watershed. After identifying CSAs, we assessed the impact of each management scenario on reducing the nutrients. Finally, based on the nutrient load reduction and the investment and operating costs of each scenario, we select appropriate solutions using a multi-criteria decision-making approach. The results showed that agricultural and pastures (livestock) land uses in Jaghin and Minab sub-basins are CSAs. In addition, Filter strips with a width of at least 10 meters and Fertilizer Reduction on Farms were recognized as the most effective strategies.