SWAT modeling – an integrated approach for the identification of critical diffuse pollution sources in the Kolleru Lake catchment, India

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Abstract

Freshwater ecosystems are facing severe threats by human activities. As a consequence of this, they can get disturbed. In developing countries, like India, freshwater lakes are endangered primarily by agricultural activities, which often accelerate erosion and the runoff. The massive application of pesticides and chemical fertilizers to agricultural lands is one reason for eutrophication in the Kolleru Lake. Industrial pollution causes deteriorating water quality and makes them unfit for drinking water to the inhabitants of the villages around the Kolleru Lake. Besides, the indiscriminate rise of fishponds across the lake is another source of pollution to the lake. The different natural and anthropogenic influences increase the highly complex ecosystem of the lake. Managing these ecosystems is a challenging task. Due to the lack of an integrated approach and comprehensive environmental policy, Kolleru Lake has been becoming an ecological crisis area. Diffuse pollution sources are still remaining. Together with inadequate management planning and actions, they are contributing to the deterioration of the water body of the Kolleru Lake. Therefore, the objectives of this study are to ascertain the priority control areas aiming at socio-economic development for the long turn protection of the lake water quality by applying the Best Management Practices (BMPs). For this purpose, the Soil and Water Assessment Tool (SWAT) was used to identify the critical areas of the lake's catchment in terms of pollution from agricultural runoff into the tributaries of the Kolleru Lake and the lake itself. Further, suggestions were provided for the implementation of agricultural management practices to minimize pollution levels.

1. Introduction

In recent decades the effective pollution abatement measures to the water quality are sizeable (Hering et al., 2010; Barton et al., 2005; Hettige et al., 1996) But, in developing countries like India, the water quality pollution levels are so high, creating existential threats to biodiversity, as well as threatening economic progress and sustainability of human lives (World Economic Forum, 2019). India is one of the foremost agriculture-based economies in the world, with high fertilizer applications and the excessive nutrients from agricultural lands, leading to prominent diffuse pollution to the surface water quality (Central Pollution Control Board, 2016; Bassi et al., 2014). The high alarming rate of increasing pollutant load of surface water from industrial accompanies is known from the concentration based discharge control of point sources, which is already an important task to control and to achieve water quality targets (Wang et al., 2004). Additionally, the reduction of diffuse pollution sources is required.

Although urbanization and demographic changes are substantial influences within the lake's catchment, land-use changes cause extreme disturbances of the catchment's ecosystems and the lake itself. Most studies demonstrate that land-use changes (Tu 2009; Zampella et al., 2007) as a driving factor for the environmental, including the physical and chemical characteristics of surface water bodies and their internal structure.

Improper management of natural resources, coupled with an ever-increasing population, is responsible for introducing many impairments of water quality threats. Most of the freshwater resources are under stress caused by urbanization, and large-scale industrialization processes are a worldwide concern (Fang et al., 2019; Holopainen et al., 2016; Liao et al., 2012).

The complexity of several ecosystem functions in the surface water bodies adversely affected foremost water quality in freshwater lakes which, in turn, and among others, influence ponds, rivers, streams and slowly enter into the groundwater (Gilboa et al., 2014; Thevenon et al., 2011; Banadda et al., 2010). Diffuse pollution caused by agricultural activities can be carried into adjacent water bodies by surface runoff and erosion (Taylor et al., 2016; Guo et al., 2010). Such excess of nutrients accelerates eutrophication and algae blooming in freshwater ecosystems. Besides, point sources are another significant reason for the deteriorating water quality in surface water bodies. However, the spatial and temporal distribution of diffuse pollutants is a challenge. It is important to monitor these distributions even for a large catchment area, due to changing climate, land-use, and strong relations to anthropogenic activities (Shen et al., 2013; Randhir and Tsvetkova 2011). Therefore, it is essential to identify the critical pollution sources of a catchment and to apply the best management practices (BMPs) to protect lake water quality.

The Kolleru Lake catchment in India has been taken as a case study for understanding and modeling of the Spatio-temporal variability in the pollutant loads, which will be a prerequisite for better management of agricultural, industrial, and water resources.

In recent decades, the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) has become widely used to model the management of agricultural catchments for identifying polluted areas. SWAT is a useful tool for the estimation of both nitrogen and phosphorus (N & P) emissions and the degree of eutrophication. Both information a necessary prerequisite for the selection of BMPs from small scale areas (Coffey et al., 2013; Shang et al., 2012; Kang et al., 2006) to large scale catchments (Abbaspour et al., 2015; Yalew et al., 2013). The U.S. Environmental Protection Agency (EPA) recognized the SWAT model and incorporated it into the EPA's BASINS (Better Assessment Science Integrating Point and Non-point Sources) (Abbaspour et al., 2015). Apart from that, several studies were extended into the SWAT-based optimization tool for obtaining cost-effective strategies for sustainable management (Liu et al., 2019; Wallace et al., 2017). However, due to continuous simulations and operations on a daily time step, it is a useful tool for the identification of pollutant sources.

The main objective of this study serves a better understanding of diffuse pollution sources in the Kolleru Lake catchment, a typical flood balancing catchment between the Krishna and the Godavari basins. Here the first study is conducted to estimate diffuse pollution in Kolleru Lake for the catchment level. Further, the study assimilated the critical sub-basin measures on the Hydrological Response Unit (HRU) level priority areas, to conclude the planning of BMPs. Furthermore, suggestions are provided for the implementation of better lake management practices in the catchment.

2. Study Area

2.1 Kolleru Lake area

The Kolleru Lake has situated between 160 24' 10" and 170 23' 44" North latitude, and 800 41' 5.5" and 810 39' 27.5" East longitude in the south-eastern part of India (Fig.1). It is the largest freshwater lake in India located in the state of Andhra Pradesh and forms the largest shallow freshwater lake in Asia, with a catchment area of 5,052 km^2, a water surface area of 901 km^{2}at +10 MSL (mean sea level). The average water depth of 1 m and a maximum water depth of 3 m can be monitored during the southwest monsoon period (Barman 2004). The minimum and a maximum temperature range from 14 0C to 22 0C from November till February and 35 0C to 46 0C from March till October, respectively. The annual mean precipitation is 1,094 mm. The lake receives water from seasonal rivers, namely, Budameru and Thammileru. Apart from this, 68 minor irrigation channels are flowing into the lake. It has only an outlet river, the Upputeru, which connects the Kolleru Lake to the Bay of Bengal. The lake has a rich biodiversity, and thereby, the international Ramsar Convention declared it as a wetland of international importance in November 2002.

The two perennial rivers of the Krishna and the Godavari formed its catchment, which gives the lake a unique characteristic and has led to its role as a natural flood-balancing reservoir between these two river basins. The catchment is also one of the most developed agricultural areas in Andhra Pradesh state, as well as the state, which is historically called the "Rice Bowl of India." With a massive fertilizer application and a high crop yield production, the Kolleru lake catchment accounts for 22.7% of chemical fertilizer consumption in the Andhra Pradesh state. According to the Andhra Pradesh Pollution Control Board (APPCB), reports that more than 17,000 tons/yr of fertilizers enter into the lake. Because of the high proportion of agricultural land and diverse agro-climatic conditions in this region, encourage the cultivation of different crops, a large number of chemical fertilizers considerably replaced the traditional organic fertilizer. In recent decades, besides the sewage inflow from nearby towns, diffuse agricultural pollution was accounted for a significant pollution source. In most cases, adding more quantities of N & P fertilizers to the soils does not result in increased crop yields and significantly led to proliferating eutrophication of the lake (Vijayalakshmi & Brahmaji 2017; Krishna et al., 2016; Bassi et al., 2014).

Kolleru lake is one of the most polluted lakes (Kolleru Lake, Pulicat Lake, Chilika Lake) in India. Therefore it is under the control of the Ministry of Environment, Forest and Climate Change (MoEF & CC), along with Central Pollution Control Board (CPCB) and State Pollution Control Boards (SPCBs). These organizations are responsible for the legal and regulatory framework for environmental protection in India (CPCB, 2005; MoEF, 2007). MoEF is accountable for the preparation of environmental policies through the Central Empowered Committee (CEC) in coordination with the Kolleru Lake Development Committee (KLDC), whereas the "Operation Kolleru" was implemented. The main objective of this voluntary program was to minimize the pollution from fishponds across the lake, the Supreme Court of India initiated the "Operation Kolleru" in 2006 to clear all encroachments and their water pollutants. It divided into three phases between 16 February 2006 and 13 June 2006. As a result, approximately 1,776 fish ponds became destroyed, and 89.08 lakh cubic meters of earth, forming tank bunds, were removed (Azeez et al. 2011).

2.2 Significance of the study

It is generally acknowledged that the following essential criteria are prerequisites for the Kolleru Lake pollution control measures and implement the adequate BMPs between point and diffuse sources:

- In the catchment, point source pollution is distinguishable. They substantially contribute to water pollution. The reduction of pollution sources should be feasible and cost-effective.;
- The rise of illegal fishponds within the lake area should be controlled and monitored;
- For reducing diffuse pollution sources must be identified and the usage of chemical fertilizers in croplands should be replaced by traditional organic methods.

Due to the lack of a comprehensive environmental policy, the Kolleru lake is still facing severe threats by, firstly, agricultural runoff. In the catchment area, paddy cultivation carried out twice a year, the first crop cultivated between July and September is known as a summer crop, whereas the second crop grown between October and March is a winter crop (Azeez et al., 2011). According to Rao (2005), the usage of fertilizers varies between these two seasons, and the first crop utilizes 40 kg/ha of chemical fertilizers and that of a second crop 120 kg/ha. Besides, around the catchment area, approximately used of 1,16, 800 tons/yr inorganic fertilizers, and one-fourth of them end up in the lake via run-off and leaching (Sreenivas and Kumar, 2013). The level of chemical fertilizer application is far beyond the maximum trend in this region, and the decrease of fertilizer application would be beneficial.

Secondly, the water quality of the lake is deteriorated by point sources; thus, untreated industrial effluents released into the lake from nearby cities (Azeez et al., 2011). According to the list of critical pollution industries of the Kolleru Lake, there are 36 industrial pollutants located in the catchment. The major industries such as rice mills, paper industries, sugar factories, milk factories situated around the lake, alternately sewage sludge from nearby cities have contributed to its depletion and pollution. The pollution sources of the lake have highlighted by several studies and still continuous effort on point source pollution control not yet implemented – the management of the Kolleru Lake wetland ecosystem has received inadequate attention in the Central Water Commission (CWC) agenda. As a result, it is subjected to severe anthropogenic pressure.

As more and more studies conducted on the Kolleru Lake ecosystem (Vijayalakshmi & Brahmaji 2017; Azeez et al., 2011; Jayanthi et al., 2006; Rao & Pillala 2001; Narender 1993), it is possible to use the accumulated information for the development of pollution control measures and their responses to environmental changes. Apart from the point and diffuse sources, damages and losses due to massive flooding during the monsoon season, and partly drying out during summertime, as a result of inadequate management planning and action, are seen as areas of improvement (RIS, 2002). These natural and anthropogenic processes are influencing the lake. Both local drivers and features originating in the whole catchment of the lake occur. Since the 1990s, the lake has gone through enormous changes; more information about these changes can be found in Azeez et al. (2011). Based on the complexity of the existing threats of the lake, first, it is necessary to identify priority or test areas for applying management practices in the Kolleru Lake catchment, at least for lake protection. This paper reports on the priority control areas aiming at socio-economic development linking with the "Operation Kolleru for demolishing the fish ponds to restore the past glory of the lake" (hereafter the "Operation Kolleru scheme") and in the long turn protection of the lake water quality by applying the Best Management Practices (BMPs).

3 Materials and Methods

3.1 SWAT model setup

The SWAT model was developed by the Agriculture Research Service of the United States Department of Agriculture (Arnold et al., 1998). This approach was adopted to simulate the diffuse pollution load in the Kolleru lake catchment. It is a physically-based and semi-distributed model that operates on a daily step and capable of continuous simulation over long periods (Gassman et al. 2007). In this study, the SCS (Soil Conservation Service) (USDA-SCS 1972) curve number was used to calibrate the surface runoff from daily rainfall data, further potential evapotranspiration from Penman-Monteith, and sedimentation from the Modified Universal Soil Loss Equation (MUSLE) (Williams 1976). The model equations are extensively documented on the official SWAT website (http://swatmodel.tamu.edu).

The data used in the SWAT model are in two different formats, i.e., from a spatial and a temporal database. Table 1 outlines the available data for the SWAT simulation. The spatial data includes the DEM (Digital Elevation Model) generated using stereo images of ASTER DEM with a spatial resolution of 30 m. Land-use data were mainly classified into agricultural land (for paddy cultivation), fishponds, urban, barren land (unused or uncultivated land), and forest areas (Fig. 2a). The soil types were categorized into 38 classes (Fig. 2b). The data provide insights into soil depth, drainage, texture, slope, erosion, salinity, etc. (Table 2). The temporal data include hydrological parameters, such as daily precipitation, maximum & minimum temperature, relative humidity, wind speed, and solar radiation. The mainly used rain gauge stations were Bhimavaram, Eluru, Gudivada, Nuzvid, and Tadepalligudem. The catchment weather information used from daily monitoring data for the period 2008-2014. Information on crop patterns, fertilizer application, fish farming, social economics, and industrial pollution was based on previous literature and data collected from local statistic yearbooks (Azeez et a.. 2011), and on-field investigations as well.

The catchment area is composed of 38 different soil types, dominantly with clayey texture. According to this data, 46.7 percent of the catchment is largely extended to the well-drained condition, 19.9 percent is moderately well-drained, while 27.8 percent is composed of imperfectly drained, and 2.4 percent is excessively drained. Very deep soils (55 percent) are predominantly identified within the catchment area, with clay dominance in texture and pore in coarse and medium pores. Present up-slope in the headwaters are covered by shrub vegetation and forest areas. The runoff from the upper catchment passes the agricultural fields of the middle part before entering into the lake. Agricultural land is the dominant land use cover (68%) of the catchment, followed by fishponds (16%), mangrove forests on gently sloped areas (10%), and the urban area does not exceed 3% of the total area.

Using a digital elevation model (DEM) with 30 m × 30 m resolution, SWAT delineated the catchment into 20 sub-basins depending on the flow direction, stream network, and drainage outlets. Slopes were classified into four gradient categories: $<3\%$, 3-5%, 5-10%, and $>10\%$. Hydrologic Response Units (HRU) derived from adjusting thresholds of 12% land-use, 15% soil, and 15% slope. There are 1,281 feature classes (HRU) that were delineated, while each HRU is being independent of the SWAT model, with a similar slope, land-use, and soil characteristics. The model was extensively calibrated against daily discharge, nitrate pollution (NO_3_N), and total phosphorus (TP) loads in the Kolleru Lake catchment.

3.2 Workflow to Action Plan

After the "Operation Kolleru," the lake water still received serious threats by diffuse pollution. Therefore, the state government authorities approved that the lake was not polluted by the fishponds, due to agricultural runoff and urban infrastructure. Kolleru Lake pollution mitigation plans were formulated between 1982 and 2015. The efforts were taken in 2006 to resolve the pollution by fishponds one site. Still, the other sources of pollution left for discussion between researchers, stakeholders, and the state government authorities. Therefore this paper reports about the identification of priority areas of diffuse pollution from 2008 to 2014 (after Operation Kolleru), based on the SWAT model (Fig. 2).

The workflow included four stages: problem definition, preparing a database and SWAT model execution, identification of priority areas, and formulation of pollution mitigation measures. The first stage included the knowledge deficit in this area, discussed with the Kolleru Lake development programs, especially with the Kolleru Lake Forest Department (KLFD), Kolleru Lake Development Committee (KLDC), researchers, and water managers. Researchers and water managers provided the necessary data for understanding and visualizing the pollution levels in the catchment. The second stage devoted to the database preparation and model execution based on the daily time step. The third stage included the identification of priority areas based on the results obtained from the SWAT model. Further, the results and necessary actions will be discussed with the researchers, stakeholders, and state government authorities. The last stage was the implementation of a measures plan protecting lake water against pollution.

3.3 BMPs setups and stakeholders engagements

The first methodological approach has identified the agricultural management priority areas for applying BMPs to facilitate the relevant information to the stakeholders. The central and state government organizations had formulated the Kolleru Lake development programs and aimed to bring an optimized solution to conserve the lake resources (Azeez et al., 2011). One such program is the Kolleru Lake Development Committee (KLDC), which checks the encroachments, regulating or monitoring the pollution level, and clearing the lake weeds every year. This study considers the agricultural runoff attributes the first time for the Kolleru Lake catchment. Thus promotes the awareness of the decision-makers and stakeholders on values, functions of the stream network, and variables of the Kolleru Lake catchment.

Furthermore, the potential outcome of the "Operation Kolleru" program aimed to restore the past glory of the lake. A priority response of an integrated water management plan (IWMP) on the catchment level became possible for an optimal set of the lake ecosystem. However, the IWMP contains an activity to enlighten the stakeholder's perception towards lake degradation. Stakeholders will become able to include Kolleru Lake ecosystem resource users, will be guided about the crucial significance of the lake functions, values, and resources from which they fulfill their needs. Moreover, the state government agencies should incorporate with the stakeholders to adopt sustainable development activities that would need a priority response.

4. Results and discussion

The results will be demonstrated on the sub-basin level. HRUs priority level of management practices is presented below. Further, suggestions were discussed to achieve the best conservation of the lake ecosystem.

4.1 Sub-basin level BMPs

The SWAT model quantified the spatial distribution of N&P emissions in the Kolleru Lake catchment. This study examined that the diffuse pollution from agricultural runoff is an essential contribution to the total loads of nitrate-nitrogen (NO_3-N) and total phosphorus (TP). According to Fig. 3a, the amount of NO_3-N is extremely different in each sub-basin ranged from 3.5 kg/ha/yr to 429 kg/ha/yr, respectively. Among the five river sub-basins, the NO_3-N was the highest in the Ramileru basin, with up to 429 kg/ha/yr in some sub-basins, and the lowest in the Gunderu basin, with less than 8.5 kg/ha/yr in each sub-basin. The average range of each tributary river basin ranked from high to low based on the load intensities is outlined in Table 3. However, the annual average load of NO_3-N in the Ramileru basin is 238.8 kg/ha/yr. The amount is larger than 40 kg/ha/yr in most sub-basins of Budameru and Thammileru. For example, 55.6% of the NO_3-N export from the entire catchment came from sub-basins No. 19, 14, 16, 13, 12, 5, 17, and 8, each contributing $>$28.7 kg/ha/yr of the areal NO_3-N export. NO_3-N in the lake mainly originates from the chemical fertilizers used in the Kolleru Lake catchment, where the agricultural land majorly accounts for paddy cultivation.

According to Fig. 3b, the spatial distribution of mean annual TP in the Kolleru Lake catchment varied from one sub-basin to another, ranging from 1.1 kg/ha/yr to 91.5 kg/ha/yr respectively. The highest TP load was established in the Thammileru basin, with up to 45 kg/ha/yr in some sub-basins, and the corresponding lowest values within the Gunderu basin, with less than 5.5 kg/ha/yr in each sub-basin. The Thammileru basin is accounted for the highest annual precipitation, which enabled the large wet deposition of P. Similar to the NO_3-N, the highest contribution of TP origin from the sub-basins No. 19, 14, 13, 11, 15, 5, 6, and 8, accounted $>$16.5 kg/ha/yr annually. The cause of the difference in sub-basin loads was observed in the Kolleru lake catchment related to human activities. Additionally, the soil data obtained from the National Bureau of Soil Survey identified that N and P distribution in the soil types do have close spatial interaction with diffuse pollution. The higher intensity load of these soils is associated with higher export amounts of pollutants from sub-basins. Therefore, this must be considered for conservation practices. Moreover, the agricultural land was disturbed by the frequent cropping and harvesting as well as by fertilizer application. The TP load from medium to maximum variation of the sub-basins is similar to the NO_3-N, which is accounted onto the mainstream channel.

The high proportion of agricultural land use has a crucial factor in NO_3-N & TP exports. Many catchments worldwide show an explicit positive correlation between N & P loss and cropland percentages (Li et al., 2018; Chen et al., 2017; Harrison et al., 2009). In the Kolleru Lake catchment medium to maximum variations of NO_3-N & TP loads in each sub-basin level was observed, following the percentage of land uses (Fig. 4). Sub-basins with a higher percentage of paddy fields result in higher N & P exports in the Ramileru and the Thammileru basins. Li et al. (2018) also show a low percentage of paddy fields, resulting in less amount of TN. However, the intensity of frequent fertilizer applications significantly impacts the sub-basins nutrient level exports and catchment characteristics as well.

4.2 Determination of HRU level BMPs

The BMPs priority areas were identified following the methodology of Izydorczyk et al., 2019, Piniewski et al., 2015) by SWAT on the HRU level as paddy cultivated lands where the amounts of NO_3-N & TP emissions are the highest. Here, the priority levels were divided into two types according to the area, which is under net irrigated, gross irrigated, and the rain-fed regions. The first BMPs priority level is the area cultivated more than once a year; emission in selected HRUs ranged from 10.5 to 28.3 kg/ha for NO_3-N, while for TP, the emission level ranged from 3.2 to 9.8 kg/ha. The second BMPs priority level is where the cropping intensity is higher than 50 % under gross cropped areas ranged from 1.2 to 10.5 kg/ha for NO_3-N, while for TP ranged from 0.5 to 3.2 kg/ha (Fig. 5a and b).

According to Fig. 5a, the majority of selected HRUs of NO_3-N were clustered around the lake area. Subsequently, they cause the eutrophication of the lake and led to increasing weed distribution. On the priority of HRUs distribution, higher NO_3-N load contributing areas were concentrated in the northern and middle-western villages of the catchment. Among them, the outstanding villages were located in the Ramileru and the Thammileru basins. In these two sub-basins, specific topographic features play an essential role in the highest NO_3-N emission. Besides, the main inflow rivers contributing the water to the lake run through these villages, are the Budameru River (5.5% of total NO_3-N in 2010), the Thammileru River (22.7% of total NO_3-N in 2010), and partially the Ramileru River (19.2% of total NO_3-N in 2010). Moreover, the diversified irrigation network canals connected to the mainstream of the river can easily extract the nutrient onto the river and nitrate loads into the lake. In contrast, the flow contribution of NO_3-N from the eastern villages are low, because of the migration ability of pollutants are limited there.

According to Fig. 5b, the TP emissions are spatially distributed and partially overlapped with the regions of NO_3-N. The majority of TP emissions are primarily concentrated in the middle reaches of the catchment. Approximately 534 village communities were located in the catchment area. Most of the regions are under gross irrigated. At certain stages, early-season drought changed the behavior of the farmers to apply the water-soluble fertilizers (NPK-nitrogen, phosphorus, and potassium), the ratio of 19-19-19, 20-20-20, and 21-21-21 to supplement nutrition. During the time, the soil absorbs the N and P to enrich the plant growth, and unleash the soluble compounds during the flooding period by surface runoff. In the catchment, topographic properties play a key role, because of moderate slopes as well as more than >46.7% of the catchment area is mostly extended to the well-drained condition, hence, nonporous in nature, contributed to high NO_3-N & TP emissions as a result of surface water runoff.

4.3 Temporal characteristics of diffuse pollutants

The annual amount of NO_3-N & TP, including streamflow, were simulated. Fig. 6a illustrates the annual distribution of diffuse pollution from 2008 to 2014 in the Kolleru Lake catchment. The distribution of the NO_3-N was very uneven between different years. During wet years higher peak values van be observed than in the dry years. The NO_3-N was relatively consistent with the runoff. Therefore, to assess the possible relation between the NO_3-N and the runoff, a simple Pearson's correlation analysis was performed. The results show a strong correlation between the NO_3-N and the streamflow ($r=0.89$, $p<0.01$), which means that the NO_3-N was primarily governed by the runoff (Fig. 6b). Hence, the result was justified with other studies (Qin et al., 2018; Navarro et al., 2014; Helmreich et al., 2010). The correlation between the TP and the runoff (Fig. 6c) is also high ($r=0.84$, $p<0.01$), but lower than the NO_3-N and the runoff. This can be attributed to the agricultural water diversion system, and a mode of severe nutrient transport. However, during the wet period (July 2010, August 2011), the runoff is relatively high and subsequently resulted in a high nutrient export, which can be transported by a stream network and accumulated near to the downstream area of the Lake. NO_3-N sources are the chemical fertilizers used in agricultural fields, especially for paddy cultivation followed by Cotton, Maize, and Chillies, in the Kolleru Lake catchment. The upward trend of NO_3-N load in June 2010, resulting from the heavy precipitation recorded during that month, according to the data derived from the Indian Meteorological Department, might be responsible for the higher nitrate export load. Industrial pollution, excessive fertilizer application, and chemical usage of fishponds to enrich the fish growth contribute in significant quantities to the nutrient loads. The primary reasons for high nutrient flow in the catchment are both frequent land-use changes, intensive paddy cultivation, and the two large rivers Krishna and Godavari.

4.4 Suggestions for pollution mitigation measures

Suggestions for adequate pollution mitigation measures can be drawn from the results of critical sub-basins and the HRU priority areas as well. This study emphasized that improved agricultural management practices are necessary for the whole catchment area. There are numerous methods to improve the agricultural practices that can be adopted by farmers to prevent nutrient losses from croplands (Izydorczyk et al., 2018). However, management practices can be targeted on agricultural lands and the development of proper land use planning and zoning practices in sub-basins. Furthermore, the implementation of buffer strips and the management of water margins to reduce surface runoff from fields are essential measures to achieve environmental improvements (Izydorczyk et al., 2018; McCracken et al., 2012, Zhang et al., 2010; Anbumozhi et al., 2005). The buffer width, the slope gradient, and the vegetation type are difficult to site conditions for designing an adequate buffer. However, an increasing buffer width would increase sediment removal efficiency (Zhang et al., 2010). Mainly, vegetated buffers are widely used for good agricultural practices to reduce diffuse source pollution from runoff (Balestrini et al., 2011). However, these effective mitigation buffer measures of nutrient losses are still rarely implemented in India (Anbumozhi et al., 2005; Bhojvaid et al., 1996).

In order to reduce the chemical pesticide consumption in Andhra Pradesh state, between 1999 and 2005, the European Union had conducted the "Non-Pesticide Management in Andhra Pradesh, India" in the cooperative project of the German Council for Sustainable Development and Centre for Sustainable Agriculture (CSA). The potential outcome of this program was to enlighten the farmers to use natural pesticides, such as neem (*Azadirachta indica*) and chili-garlic extracts, rather than intensive use of chemical fertilizers. Therefore, the positive results caused increased biodiversity, no adverse environmental effects, preventing soil erosion, and improving soil fertility. This study further suggests the implementation of the "Non-pesticide management" practices in the Kolleru Lake catchment. However, this kind of institutional practice for empowering rural people, imparting training to farmers, and laying demonstrations are essential for sustainable management growth. Besides, the catchment comprises of 534 villages, and not even more than >20% adopted the conventional irrigation methods. Moreover, this study identified the HRUs level priority areas along with critical sub-basin measures, which should be analyzed and implemented. For minimizing the environmental crisis, also a forest area has suggested around the 3ft contour level of the lake. Thus, it provides shelters for the 20 million immigrant, international birds as well as to conserve the environmental lake ecosystem.

Additionally, the Government of India notified that only the traditional method of fishing activities should be permitted around the lake, following the law of G.O.Ms.No.120, dated 4.10.1999. For this purpose, the Kolleru Fisherman Cooperative Society (KFCS) should adhere to the standards laid down by the Ministry of Environment, Government of India, to bring back the Kolleru Lake to its near pristine condition. Moreover, adequate steps should be taken for stoppage and regulation of industrial pollutants from nearby towns. Furthermore, the villages surrounded by the lake must be classified as zones for BMPs.

4.5 Limitations

Because the Kolleru Lake catchment is an ungauged type, sufficient calibration, and validation of the SWAT model are limited. Unfortunately, there exists still a lack of observed data for nutrient load, especially for the discharge depending on nutrient load. However, the study was conducted based on original data, acquired from Indian Organizations, promising the results obtained from the SWAT model. This is the first study conducted for the whole Kolleru Lake catchment level, regards certain assumptions that were made in terms of catchment delineation boundaries and the crop fertilization period. Field investigations on the interaction of pollutant loads with the runoff should be taken into consideration for a better calculation of the pollutant load.

5. Summary

From the above-mentioned suggestions, it can be concluded that the management of agricultural practices is required to adapt to the whole catchment region. The essential features of nutrient runoff from croplands should be taken into consideration for the protection of the lake water quality. Pollution abatement methods, continuous monitoring of point sources pollution, and laying demonstrations to enlighten the public perception towards lake degradation would be beneficial.

This paper serves as an initial discussion of the diffuse pollution in the Kolleru Lake catchment. The results of SWAT modeling showed that 28% of the highest NO_3-N load contributed from the Ramileru basin, and 32% of TP load from the Thammileru basin, which make them to the critical river basins of diffuse pollution. Among them, the average load of individual sub-basins is estimated. This study indicated that diffuse pollutions are mainly governed by agricultural runoff. Apart from that, HRU priority level critical sources of NO_3-N and TP were identified against the village communities. Besides, the first and second priority levels of BMPs of diffuse sources were highlighted. These results improve the understanding of pollution levels and targeting control measures of critical priority areas in the Kolleru Lake catchment. The communication between the stakeholders and water quality managers are required for knowledge exchange. This is a basis for a profound understanding of the ecological crisis of lake degradation levels, and a prerequisite for the development of further implementation measures.

Data availability statement: The authors would like to share the data based on request.

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