WATER QUALITY MODELLING AND IMPROVEMENT OF WATER SAFETY OF RAMBAKAN OYA RESERVOIR CATCHMENT IN MAHA OYA IRRIGATION DIVISION

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WATER QUALITY MODELLING AND IMPROVEMENT OF WATER SAFETY OF RAMBAKAN OYA RESERVOIR CATCHMENT IN MAHA OYA IRRIGATION DIVISION

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Abstract: The Rambakan Oya reservoir is the primary water source for the Maha Oya water supply scheme and provides irrigation for paddy cultivation. In early 2020, this reservoir was highly affected by algal blooming throughout its catchment area. Therefore, this comprehensive study was conducted to identify the sources of pollutants and propose water safety plans for the Rambakan Oya reservoir catchment. Water samples were collected from twenty different locations on the surface of the reservoir, by taking into account the outlets of streams to the reservoir. The results indicated that Nitrite, Chemical Oxygen Demand (COD), and total coliform are the most potential pollutants beyond the safe level for drinking water. To analyze the potential pollutant loading based on various land use patterns, the Storm Water Management Model (SWMM) was employed. Moreover, using a hazard matrix analysis, all potential hazards, both visible and hidden that could contaminate the water in the reservoir were thoroughly investigated by module number three of Water Safety Plans (WSP). The findings show that the potential pollutant loading at critical outlets increased with deforestation, while the impact of development activities on pollutant load was relatively insignificant. On the other hand, forest extent of 30% only affected a 5% increase in pollutant loading. These findings highlight that the primary cause of the undesirable impact on the Rambakan Oya reservoir is the runoff from cattle farms, carrying water contaminated with fecal matter and urine, rather than land development activities. Moreover, surface runoff generated from agricultural lands and fecal pollution due to domestic effluents is in the next higher-order level of risk. Therefore, risk mitigation measures alone cannot ensure the safety of the reservoir, the contribution and support of stakeholders are also crucial to enhancing the safety of the Rambakan Oya reservoir.

Keywords: Algal Blooming; Land Use; Pollutant Loading; Stakeholders

1. Introduction

Rambakan Oya reservoir is the main water source to provide water to a water supply scheme of Maha Oya and to irrigate the cultivation lands, mainly of paddy in Maha Oya irrigation scheme (Deshapriya, 2017). In early 2020, this reservoir was highly affected by algal blooming over the entire reservoir surface. Several courses were identified however, a valid course of this issue has not yet been verified. This triggered many institutions to be involved in this issue to identify the sources and to propose effective solutions.

Water quality modeling tools are generally used to estimate the water quality under different scenarios and these models allow decision-makers to make decisions accordingly to provide sufficient quality of water to the end users. A wide range of water quality modeling tools are used across the world. However, the choice of a specific tool depends on the water quality issue at hand, as outlined in the handbook prepared by the World Bank (1999). In this study, the Storm Water Management Model (SWMM 5.2), a hydrodynamic and water quality model, was applied to assess potential pollutant loading to the reservoir under different scenarios.

Collective use of water quality modeling tools and hazard analysis led to the end of a final decision for a catchment safety plan interested in this study. Therefore, risk assessment was carried out based on a semi-quantitative approach, and eventually, the catchment safety plans for the Rambakan Oya catchment were proposed based on guidelines recommended by WHO.

2. Materials and Method

2.1 Study Area

The Rambakan Oya reservoir is located in the Ampara district of Sri Lanka and falls under the jurisdiction of the Maha Oya Irrigation Division. The reservoir with a capacity of 45,500 acre-feet, serves the purpose of irrigating cultivated lands and supplying water to a water treatment plant in the nearby town of Maha Oya. The catchment that drains the water to the reservoir has an area of 130 km^2, primarily consisting of forests (Tech, 2018). It has been estimated that 2,300 families are benefited from the reservoir. Figure 1 shows the catchment boundary of the Rambakan Oya reservoir.

Figure 1: Rambakan Oya reservoir catchment boundary.

The catchment area is largely covered by gravelly soil, and the sandy clay loam-type soil was to some extent. Moreover, the elevated locations in the eastern part of the catchment had gneiss rocks. The climate of the catchment was calm in the morning and evening and a heavy windy condition was observed in the noon, as it could not reach the middle of the reservoir.

People dwelling in the catchment area belonged to the indigenous community, and during field visits, small-scale sugarcane cultivation near their houses was observed. China and home garden activities were in some locations within the catchment however, paddy cultivation was not observed upstream locations of the reservoir. It is noteworthy that a substantial portion of the catchment, excluding locations far upstream of the reservoir, is covered by dense forests that serve as habitats for wild animals, including elephants and various bird species.

2.2 Water Sampling

Water samples were taken from twenty different locations on the surface of the reservoir, as depicted in Figure 2, taking into account the outlets of streams to the reservoir. A canoe was used to reach the points and collect the water samples. A GPS unit was used to record the coordinates of sampling points. Before sampling, the sampling containers were thoroughly washed with the water to be sampled. The collected samples were labeled, sealed tightly to prevent air and water entry, and transported to the laboratory in an ice box/ Upon arrival, they were stored in the refrigerator at 4^0C to deactivate microbial functions.

Figure 2: Sampling locations.

2.3 Testing of Water Samples

Immediately after the sample collection, the water quality parameters such as dissolved oxygen (DO), pH, and Temperature were measured in the field using the testing methods listed in Table 1. Additional tests were conducted in the laboratory, and the testing methods for these are provided in Table 2, as specified in the source by Demand (2012). The values of all tested parameters were compared with the standard allowable limits outlined in the source Water (2012).

Table 1: Testing methods of water quality parameters in the field

Water quality parameters	Testing methods
DO %concentration (ppm)	Portable Multiparameter (HANNA, HI9829)
pH	pH meter (HANNA, HI1271)
Temperature (°C)	Thermometer

Table 2: Testing methods of water quality parameters in the laboratory

Water quality parameters	Testing methods
BOD	5-Day BOD test
Nitrite	Spectrophotometer (HACH, DR5000)
Phosphate	Spectrophotometer (HACH, DR5000)
COD	Spectrophotometer (HACH, DR6000)
TSS	Oven dry method
TDS	Oven dry method
Total Coliform	Membrane filtration method
Turbidity	Turbidity meter (HACH, TL2350)

2.4 Risk Assessment

On-site visits, questionnaires, and historical records were used to gather comprehensive information on hazards and hazardous activities related to chemical (C), physical (P), and biological (B) hazards. A questionnaire form was developed for conducting interviews with stakeholders of Rambakan Oya reservoir, and the survey was completed.

The risk matrix was created using a semi-quantitative methodology. The consequences or severity of a particular hazardous event were graded on a scale of 1 to 5, with 1 indicating the least impact and 5 indicating the most impact. Similarly, the likelihood or frequency of occurrence for a given hazardous event was graded on a scale of 1 to 5, with 5 indicating the highest frequency.

The following Eq. (1) was employed to determine the overall risk for a specific hazardous event based on the severity and likelihood score/rating:

$$\text{Risk Score} = \text{Severity rating} \times \text{Likelihood rating} \quad (1)$$

The risk band range for a specific hazardous event was taken in the hazard analysis matrix at the following intervals depending on the risk score:

a) Low (L) : 1-5 (denoted by green colour)
b) Medium (M) : 6-15 (denoted by yellow colour)
c) High (H) : 16-25 (denoted by red colour

2.5 Modelling and Simulation

Figure 3 shows the modeling process in a simplified flow diagram.

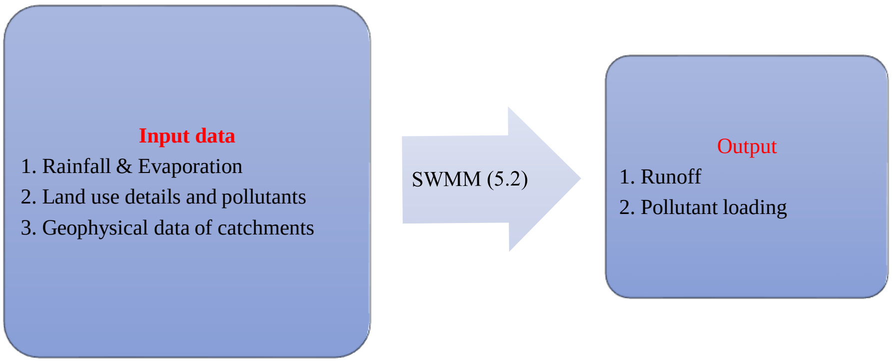


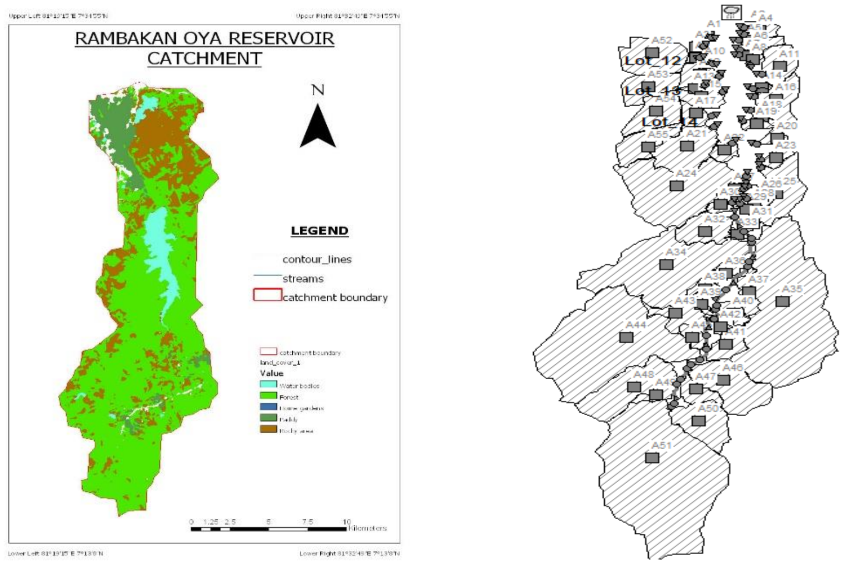
Figure 3: Simplified modelling process.

2.5.1 Rainfall and Evaporation

Daily average rainfall data, reflecting continuous precipitation over three years, was obtained from the Department of Irrigation of the Maha Oya scheme. Evaporation data, obtained from the Department of Meteorology, was also utilized as input to run the model. Monthly averaged values of evaporation for the Maha Oya region in the year 2019 were considered for this study.

2.5.2 Land Use Details

Land usage within the Rambakan Oya reservoir catchment was obtained from the Department of Land Use and Planning of Sri Lanka for the year 2018. The catchment of the Rambakan Oya reservoir is predominantly characterized by dense forest area. Additionally, recent land development activities carried out in 2020 were identified and delineated in ArcGIS with advice from the Department of Irrigation in Mahaoya. The utilized land use pattern is depicted in Figure 4(a). Lots 12-14 are newly developed plots for cultivation purposes, and they are shown in Figure 4(b) along with other sub-catchments.



(a) (b)

Figure 4: (a) Land use patterns of reservoir catchment (b) Developed land plots.

2.5.3 Geophysical Data of Catchment

Catchment discretization was at the initial stage of modelling. This was carried out using catchment delineation process in Arc GIS Pro. In addition to the catchment delineation, possible stream inlets to the reservoir from each delineated sub-catchment were also identified according to the source Vieira (2014). In general, for the better catchment delineating, GIS requires high quality digital elevation model data (DEM). A 30 m DEM data was obtained from the United States Geological Survey (USGS) website. Moreover, catchment discretization was achieved in the SWMM as shown in Figure 4 (b).

2.5.4 Pollutants

The input required for simulating water quality was integrated with land-use details of the sub-catchments. SWMM necessitates pollutants as inputs, and these should be assigned to each land use. The most potential pollutants, namely nitrite, COD, and total coliform, were identified based on the analysis of the test results and assigned for the pollutant input.

Pollutants belonging to each sub-catchment require buildup and wash-off functions. However, the selection of these functions has numerous options and must be determined through experiments. In this study, the exponential function (EXP) was utilized to formulate the pollutant buildup and wash-off (Haughey, 2021).

2.5.5 Model Outcomes

Sub-catchments in the western part of the reservoir contain critical locations where higher pollutant loading is experienced. It is possible to discern the pollutant loading pattern at an outlet. J32 is an outlet that accumulates pollutant loading from recently developed land lots (Lots 12 and 13), whereas J37 accumulates from Lot 14. Initially, all sub-catchments and land development lots were considered to be 70% forest and the remaining 30% as land developed.

It was observed that both outlets had a similar nitrite loading pattern, reaching a maximum of 2.5 mg/L. COD loading in outlets 32 and 37 was also similar, with the maximum concentration attained for the considered rainfall being 22.5 mg/L. Total coliform loading in outlet J32 was 10,000 CFU/100 mL, while for outlet J37, it was 200 CFU/100 mL.

The percentage of land use was changed later to figure out the pollutant loading pattern in each outlet considered in this study. A 40% reduction in the forest area which was 30% of forest and 70% of land development was assigned to determine the new loading pattern for pollutants The results obtained for the nitrite loading show that 40% increase in the deforestation in Lot 12, 13 and 14 coursed an increase in the nitrite concentration which was about 1.0 mg/L at outlet J32 and about 0.5 mg/L at outlet J37. The result obtained for the COD loading belongs with 40% of deforestation in Lots 12, 13, and 14 illustrating that there was a 5 mg/L increase in the COD loading at J32 and no significant increase in the COD loading at J37. This shows that a 40% reduction in the forest land had raised the total coliform counts by 1000 CFU/ 100 mL at outlet J32. However, there was no significant change in total coliform counts at outlet J37. In this way, all sub-catchments were accounted to have a percentage reduction in forest area, and consequent pollutant loadings were examined.

The results obtained for different land use patterns assigned to estimate potential pollutant loading at critical outlets show that pollutant loadings increase with deforestation. However, the rate of increase in pollutant load with the escalation of development activities is insignificant. On the other hand, a 30% reduction in forest coverage resulted in a 5% increase in pollutant loading. This suggests that the primary cause of this undesirable impact on the Rambakan Oya reservoir is not the land development carried out. Runoff from cattle farms, carrying fecal matter and urine-contaminated water, could be the source of this stress on the reservoir.

3. Hazard Analysis

It can be recognized that high risks are associated with algal blooms and cattle farms, particularly with excessive cattle in the pasture. According to the analysis of test results by Balasooriya (2005) and Suja (2019), it is suggested that the high levels of fecal coliform and nitrite contaminants in the reservoir are due to the presence of cattle in the catchment. Therefore, immediate mitigation measures should be implemented to prevent pollutant loading from entering the reservoir, as recommended by the source Science (2022).

Surface runoff from agricultural lands and lands lots developed for further cultivation activities, deforestation, and fecal pollution from domestic effluents pose medium-level risks. This category of risks should be carefully monitored and minimized to prevent their respective risk rates from reaching a high-risk level. Remaining medium risks, with a lower probability of escalating to high risk, can be progressively minimized by implementing mitigation measures. Low-level risks, in fact, no longer have a significant impact on the reservoir water quality; furthermore, they will no longer require any mitigation measures if proper monitoring programs are established (Hoybye, 2002).

According to the Guidelines for Drinking Water Quality, developed by the World Health Organisation (2022), improvement plans are being proposed in the appropriate format by Water Safety Plans (WSP) for the hazardous events that are on the higher side. Even if the risk band is already under control, the improvement strategies are still recommended as mentioned in Table 3.

Table 3: Proposed control measures for each hazardous event

No	Hazard type	Hazardous Event	Likelihood	Severity	Risk Rating	Risk Band	Basis (Reason for selection of Likelihood and	Proposed Control Measures	Likelihood	Severity	Risk Rating	Risk Band
1	P, M	Algal bloom	4	5	20	H	Observed	1. Aeration 2. Ultrasonic algae control	1	5	5	L
2	P	Human activities	5	2	10	M	Indigenous people living around this reservoir	1. Strictly prohibiting. Unauthorized access. 2. carrying out awareness programs and legal action	3	2	6	M
4	P	Bathing, washing, and swimming	4	2	8	M	Habits of the surrounding people	Regular inspection and carrying out awareness programs	2	2	4	L
5	P, C	Fishing	5	2	10	M	Fishing area	Taking Legal action against prohibited activities	2	2	4	L
6	P, M	Soil erosion during rain	3	3	9	M	Observed during the rainy season	Creating buffer zones around the water body	1	3	3	L
7	P, M, C	Surface runoff from agricultural lands	3	5	15	M	This may happen in the rainy season due to stormwater runoff	Introducing organic farming and Introducing new crops that need a lesser number of fertilizers and other chemicals	1	5	5	L
9	P, C	Bush-fire in catchment	2	3	6	M	Information given by NWSDB	Introducing training courses on planning and implementing controlled fire	1	3	3	L

10	P, M	Picnic and camping	2	2	4	L	May happen	No control measures	2	2	4	L
11	P, C, M	Discharging from industries	1	2	2	L	No industries within the catchment area	No control measures	1	2	2	L
12	P	Unauthorized garbage disposal	1	3	3	L	Not observed	No current control measures	1	3	3	L
13	P, C	Off-road vehicle washing (tractors)	3	2	6	M	Development activities are going on	carrying out awareness programs and Legal action	2	2	4	L
14	P	Religious activities	1	1	1	L	Not identified	No control measures	1	1	1	L
15	C, M	Contaminants in stormwater runoff	3	4	12	M	This may happen in the rainy season due to stormwater runoff	Open channel with sorption material and hydrophilic plants	1	4	4	L
17	P, C	Corrosion of gates and mechanical parts	2	2	4	L	Observed during visit	Anti-corrosion measures (Painting)	1	2	2	L
18	P, C, M	Effluents from the treatment plant	1	1	1	L	Not discharged here	No control measures	1	1	1	L
19	P, M	Runoff from cattle farms	5	5	25	H	Information given by officials of WTP, NWSDB	Relocating of cattle farms to downstream and Introducing better treatment procedures	2	5	10	M
20	P, M	Dead animals	3	2	6	M	Nature and habits of the people	Regular inspection and carrying out awareness programs	2	2	4	L

22	C	Bottom sediment activation	3	3	9	M	Records	Construction of pipelines directing the waters of the surface to the bottom	1	3	3	L
24	P	Deforestation	3	4	12	M	Information given by relevant officers	Legal action	1	4	4	L
25	P, M	Excess cattle	5	4	20	H	Causes of fecal pollution	Fencing around the water body	3	4	12	M

5. Conclusion

This study was carried out to investigate the water quality of the reservoir and propose a catchment safety plan through water quality modeling and risk assessment processes. Raw data for reservoir water quality was obtained through sampling in various locations across the surface of the reservoir. Tests conducted on various water quality parameters, pollutants, and pollutant indicators revealed potential impacts on the reservoir, particularly in terms of total coliform, nitrite, and COD loading.

Critical locations identified from the analysis of test results were integrated into the model to quantify pollutant loading under various land use scenarios. In collaboration with the modeling, a risk assessment was conducted to rate risks and propose mitigation measures. It was concluded that high risks were associated with runoff from cattle farms, as there was no significant change in pollutant loading despite significant changes in land use patterns. Immediate mitigation measures, such as relocating the farms and adopting integrated farming practices, are necessary. An algal bloom was identified as another high-risk factor based on the risk assessment process, indicating the need for increased attention to runoff from agricultural lands. The promotion of organic fertilizers should be considered to further reduce this risk.

However, risk mitigation measures alone cannot ensure the safety of the reservoir water. Therefore, it is imperative to develop an efficient catchment safety plan involving stakeholders from the community-based association of indigenous people in Polbedda GN division, farm landowners, and Pradeshiya Sabha, Polbedda.

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