Multi-Temporal GIS-Based Analysis of Surface Water Susceptibility to Pollution in the Kala Oya Basin, Sri Lanka

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***Abstract* - This research focused on identifying pollution-prone areas within the surface water bodies of the Kala Oya basin and developing a Surface Water Susceptibility Index (SWSI) to assess their vulnerability to contamination. The SWSI maps were developed using six main parameters: streams, soil type, ground slope, settlements, land use, and the road network. These factors were analyzed using Arc GIS 10.8 software and the real time data were obtained through sample surveys in 2019. To integrate these multiple parameters, the Multi-Criteria analysis (MCA) was conducted, using the weighted linear combination technique (WLC). This approach enabled a systematic categorization and aggregation of each criteria where its importance is ranked then integrated using expert opinion and review of related studies. The applicability of the SWSI model was further assessed using Inverse Distance Weighted (IDW) interpolated real time water quality data obtained for the Kala Oya basin. The research identified that the pollution risk was moderate in the basin area and it occupied 34.92 % of the total basin area with the lower and the upper basin having a relatively low pollution risk. From the map removal techniques, it was found out that sensitivity of surface water to pollution is more influenced by slope then by soils, road, LULC, and settlement and streams in order. This research calls for specific pollution controls geared towards the sensitive features already distinguished. These findings are evidence that support the measures of pollution control and also is a pointer to how best water quality could be managed for the best results fits most effectively the local water management and land use.**

Keywords: Surface water, Susceptibility, Pollution SWSI model, Multi-criteria Analysis (MCA) and weighted linear combination (WLC).

I. INTRODUCTION

Surface water is recognized as one of the important natural resources that main important role of stability of ecological systems, water supply for human consumption as well as supplies water for agricultural practices [1]. Currently, surface water is just about 0.3% of the global freshwater resource, with a slight increase over the last decade [2]. Globally, these resources represent significant portion of the world land and are important sources for various activities. However, surface water bodies are continuously shrinking and being polluted, degrade by various destructive phenomena [3]. The availability and quality of surface water are of furthermost importance for human and other living organisms, and their surroundings [4]. But these significant water sources are experiencing pollution risks due to various forms of destructive activities such as agriculture practices, industrial effluent discharges, domestic sewage, and uncontrolled urbanization. Thirdly, contamination is worsened by climate factors including drought and flash floods for these resources [5]. The adverse consequences of pollution of surface water bodies, decreased water quality, diminished biodiversity, and increased risks to public health and environmental sustainability [6]-[8].

Surface water pollution has become a serious issue now [9]-[11]. It is essential to increase awareness about susceptibility to pollution or risk zones and raise public understanding of pollution exposure areas must exist alongside education about preventive measures. The combination of remote sensing (RS) and geographic information systems (GIS) enables exact mapping of surface water susceptibility which delivers an essential platform for robust surface water resource management [12]. These technologies serve triple functions for information analysis and decision-making support as well as data collection and storage in operational settings with spatially significant decisions [13]-[15]. Many researchers worldwide have developed Surface Water Susceptibility to Pollution Index (SWSI) in recent years using RS and GIS techniques [16].

SWSI has been extensively analyzed in previous studies by key researchers [16], [17]. Their major findings have added significant value to the comprehensive understanding of water quality dynamics of river basins [16]. Eimers *et al.*[18] consisted of an overlay and index-based approach that would measure watershed features based on a combination of five individual parameters. Another susceptibility assessment approach developed by Gallegos *et al.*[19] relies on seven catchment-specific parameters including wastewater discharge and vegetation cover. University of Minnesota-Duleth, USA's Laboratory for Spatial Analysis and the Geosciences has developed initial methodology in 2003 using four inherent factors to assess the surface water vulnerability to pollution from non-point source using the law of susceptibility that landscapes at risk of runoff can carry suspended sediments to body of water [20]. The rainfall is also an important parameter to cause soil erosion. Some researchers use rainfall data for modeling approach [14]. Harum *et al.*[21] have defined susceptibility of surface water to pollutions using different parameters including river network, soil, urban distribution, land cover and slope. Al-Harahsheh *et al.* [22] used a methodology that was originally developed in U.S. lab in 2003 and it adopts four major parameters which include gradient slope, proximity to surface water bodies (streams and lakes), land cover characteristics, and soil properties that were used to determine the susceptibility to surface water within a catchment area. In northern Jordan, a susceptibility assessment of surface water contamination to six determining factors (integrated within a GIS-based Weighted Linear Combination (WLC) framework) was performed by Al-Adamat [16]. Through the outputs of spatial analysis and defined criteria of classification, the resulting susceptibility map was divided into four categories: Low, Moderate, High, and Very High [16].

Surface water quality pollution has become increasingly frequent in Sri Lanka in recent years due to anthropogenic activities [22], [23]. However, limited attention has been directed toward assessing the probability of surface water pollution in Sri Lanka's river basins [24]. Such gap at the local level highlights the importance of the localized assessments to enable evidence-based water resource management and policy response. [25], [26]. In this study, a SWSI map was developed using remote sensing and GIS techniques to identify potential surface water pollution risk areas for 2019. According to the author's knowledge, this research is the first of its kind to create a complete map of surface water Susceptibility to pollution in the entire Kala Oya basin in Sri Lanka, through the use of combined remote sensing techniques and GIS mapping tools.

This research mainly aims at determining the pollution risk areas in the surface water bodies of the Kala Oya basin and coming up with a Surface Water Susceptibility Index (SWSI) to determine the Susceptibility of surface water to pollution in the Kala Oya basin. The proposed research would be a reference to guide future water quality monitoring and decision-making frameworks. Along with the main objective, the research aims at figuring out the major natural and anthropogenic factors of surface water susceptibility to pollution, carrying out a multi-temporal analysis for the water quality in an any river basin and describing, assessing the spatial density of pollutants and proposing a GIS-based index that indicates a comprehensive investigation of susceptibility in different environments of hydrology. Sharing of this essential geospatial data promotes community awareness on surface water susceptibility in these risk areas of pollution to employ preventative measures to mitigate environmental hazards and protect the surrounding environment and people affected.

II. MATERIALS AND METHODS

A. *Study area*

The selected study area which is represented from Figure 1 for this research is Kala Oya basin that is located between Northern latitudes 07° 034′ and 08° 023′ and Eastern longitudes 079° 051′ and 080° 045'.The basin is elongated with a length of about 150 km and width of 25 km nearly in the middle of this length. It is around 2,870 km2 in area and 76% of the basin is positioned in the northwestern dry zone of Sri Lanka [23]. Its elevation differs from sea level to 600 m above mean sea level at its headwaters and covered North-Western, Central and North-Central provinces of the country. The Kala Oya basin is normally subjected to a mean rainfall of 1450 mm yearly, mostly from December to February during the North-East monsoon. Kala Oya river basin processes the third longest river in Sri Lanka [26].

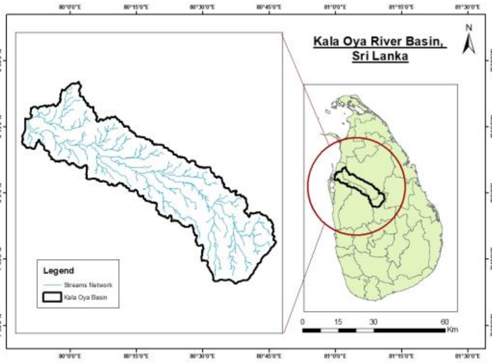


Figure 1. Study Area

B. *Surface water susceptibility to pollution influencing factors*

The surface water susceptibility to pollution is influenced by a range of environmental and anthropogenic factors, including soil characteristics, topographic slope, land use & land cover, proximity to stream networks, road infrastructure, and human settlements. However, in this study, the authors have focused, on those most commonly acknowledged determinants that have been defined in the earlier studies on the matter and that turn out to be always relevant in explaining pollution dynamics within the realm of river basins [18], [26]. Based on this, the following variables were included in the development of a spatially explicit index to assess susceptibility to pollution of surface waters within the Kala Oya basin.

Slope is a critical physiographic factor influencing the surface water susceptibility to pollution [16]. This paper used slope data that were extracted using a 30 meters spatial resolution Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM). The stream network of the Kala Oya basin was generated using the Hydrology toolset in ArcMap 10.8 based on DEM. The land use/land cover map of the Kala Oya basin was created using Landsat 8 OLI imagery in 2019, less than 10 % cloud cover, which is acquired using the USGS Earth Explorer tool in 30 m x 30 m resolution. The classification process encompassed six distinct categories, namely water bodies, forests/vegetation, bare lands, settlements, agriculture and cloud cover. In order to attain this classification, there was the use of a nonparametric supervised approach as shown in Figure 3. To evaluate the accuracy of the land use/land cover (LULC) classification, 63 randomly selected sample points were overlaid on Google Earth imagery. Among them, 45 points were correctly classified, resulting in the overall accuracy of 71.43%, a high degree of classification reliability. The calculated kappa coefficient (Khat (1)) equal to 0.63 demonstrates the substantial agreement according to the criteria suggested by C. Schmidt and A. McCullum [27].

$$K = \frac{N\sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r}(x_{i+} \times x_{+i})}{N^2 - \sum_{i=1}^{r}(x_{i+} \times x_{+i})} \quad (1)$$

N; Total observations in the matrix

r; Rows and columns in the matrix

x_{+i}; Marginal total of column

x_{i+}; Marginal total of row

x_{ii}; Number of observations in row i and column i

The soil map for the South Asian region was obtained from the FAO/UNESCO Soil Map of the World database. To increase the spatial specificity, national soil map of Sri Lanka was included as classifications of details. Settlement and main road network maps were digitized based on visual interpretation of the 2019 Google Earth imagery. Stream, road, and settlement factors were buffered into five categories as defined in Table I. Surface water bodies near roads, streams and settlements are more prone to pollute and at a greater risk [28]. The ranking of input variables based on their pollution sensitivity, ranging from 1 (very high risk) to 5 (very low risk),

C. *Data Analysis*

Equation (2) presents the governing formulation of the modified Surface Water Susceptibility Index (SWSi).

$$SWSI = w_1 \cdot S + w_2 \cdot SW + w_3 \cdot L + w_4 \cdot R + w_5 \cdot N + w_6 \cdot T \quad (2)$$

These factors include slope, stream wades, land use and cover, road networks, settlements and soil type represented by S, SW, L, R N and T respectively and where (w_i) represents the weight attached to each of the factors.

The overall index calculation could be classified into 5 susceptibility classes as listed in Table II (Very Low, Low, Moderate, High and Very High).

A developed model of a new SWSI was validated by comparing with the 2019 measured Water Quality Index (WQI) data gathered within the Kala Oya river basin with the both wet and dry season's results. WQI were calculated by using weighted arithmetic water quality index method [26], [29]. The overall procedure for developing the SWSI map is illustrated in Figure 2.

TABLE I. Summary Table of Weights and Ratings

Factor	Category	Rating	Weight
Ground Slope (GS) (%)	0-2.43	1	6
	2.43-06.63	2	
	6.63-14.47	3	
	14.47-24.94	4	
	24.94-69.86	5	
Streams (Distance to stream- DS)	< 50	5	5
	50-100	4	
	100-200	3	
	200-500	2	
	> 500	1	
Soil (Type of soil- SC)	Red - Yellow Latosols	1	3
	Reddish Brown Earth & Solodized Solonets	2	
	Reddish Brown Earth & Low Humic Gley soils	3	
	Reddish Brown Earth gravel in subsoil (M)	4	
	Erosional remnant with eroded shallow soil	5	
Land use/Land cover (LULC)	Bare Land	1	4
	Vegetation	2	
	Settlements	3	
	Agriculture	4	
	Water Bodies	5	
Settlements (Distance to settlement- DSE) (m)	0-100	5	2
	100-500	4	
	500-1000	3	
	1000-5000	2	
	> 5000	1	
Distance to Roads (DR) (m)	0-500	5	1
	500-1000	4	
	1000-2000	3	
	2000-5000	2	
	> 5000	1	

Athapattu *et al.*[26] presented two WQI maps of Kala Oya basin for the two seasons. As evidenced of that, WQI values were comparatively higher during the wet season than dry season. According to the results, a weighted approach was followed to compile the final map of Water Quality Index (WQI) where the values of 0.55 and 0.45 were applied to the wet season and the dry season respectively, thereby indicating the relative influence of seasonal variability on surface water conditions.

$$WQI/WS\ (0.55) + WQI/DS\ (0.45) = WQI \quad (3)$$

Where,

WQI; Water Quality Index

WS; wet season

DS; dry season respectively.

Sensitivity analysis was conducted based on the map removal sensitivity analysis test [16], [30].

$$MAD = \frac{1}{n}\sum_{i=1}^{n}[V_{base} - V_{modified}] \qquad (3)$$

$$SI - \frac{100\ x\ MAD}{Mean\ Value\ of\ Base\ Map} \qquad (4)$$

Where, MAD; Mean Absolute Difference, n; Total number of cells in the raster, V_{base}; Susceptibility value of a cell in the base model, $V_{modified}$; Susceptibility value of the same cell in the modified model, SI; Sensitivity Index [16].

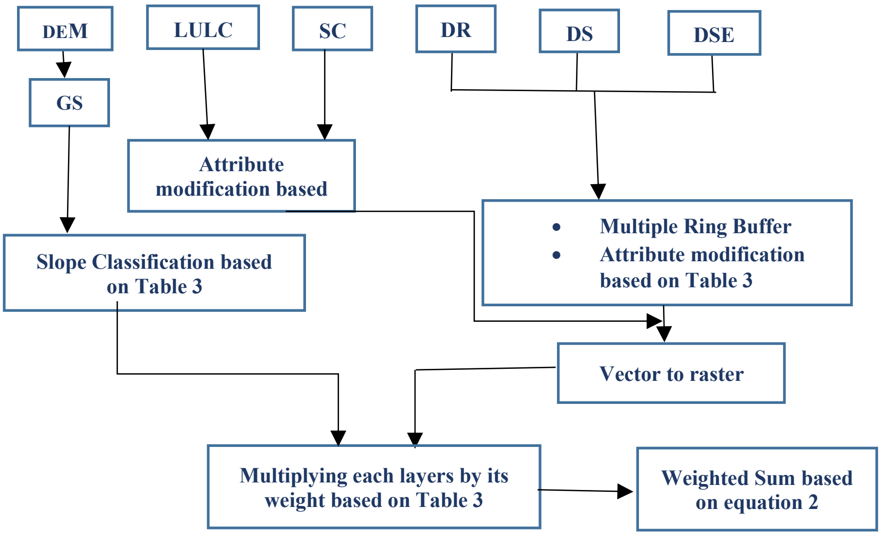


Figure 2. The adopted methodology for data analysis.

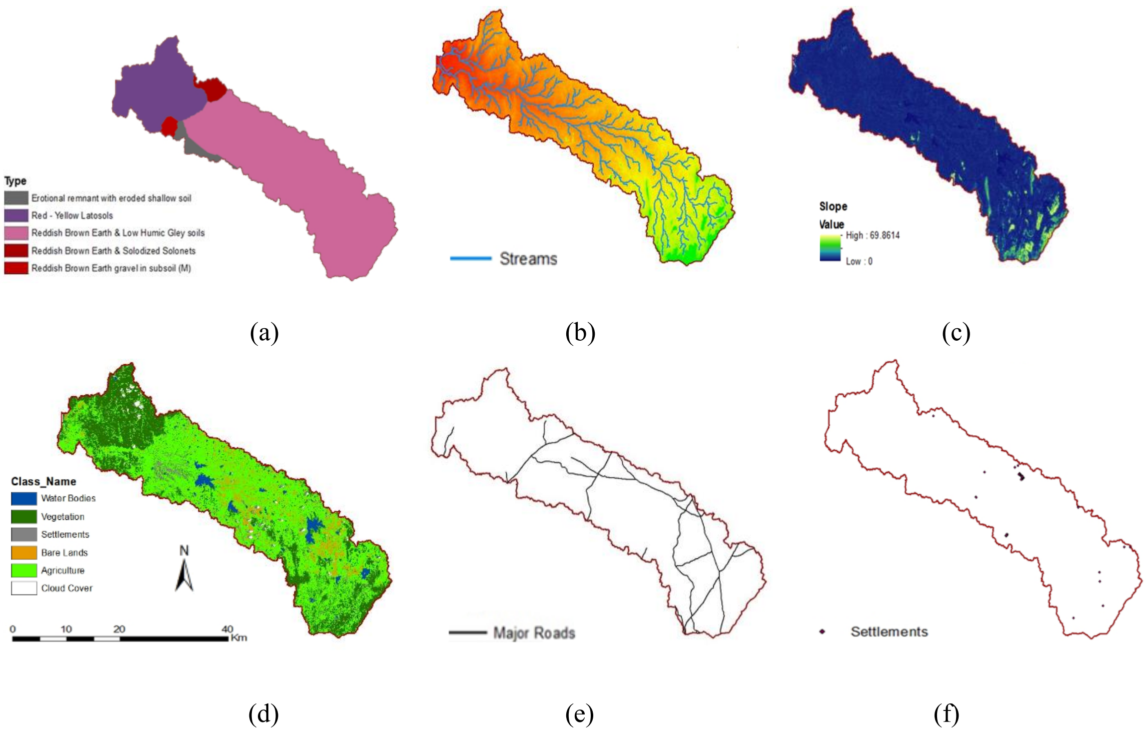


Figure 3. Surface water susceptibility to pollution influencing factors in Kala Oya basin, Sri Lanka (a) Soil types (b) Streams (c) Slope (d) Land use/ Land cover (e) Major roads (f) Settlements

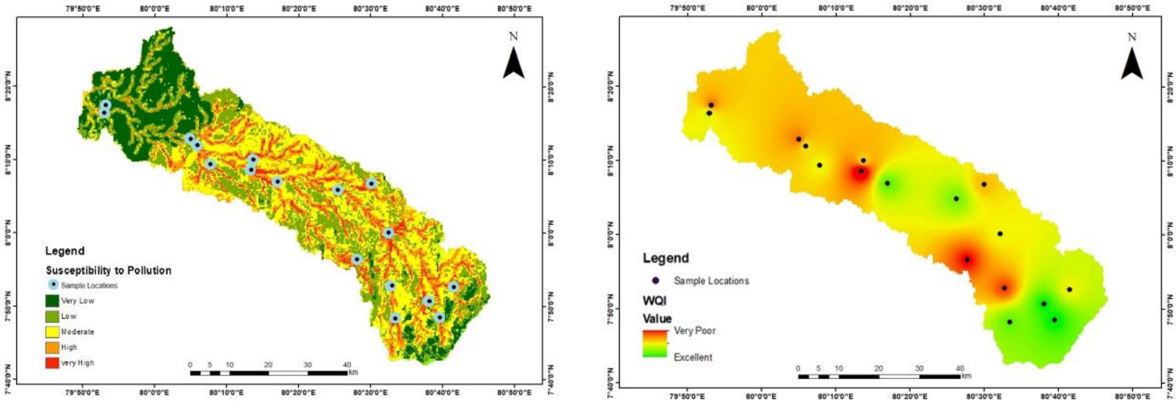
III. Results & Discussion

The Surface water susceptibility to pollution index (SWSI) model was developed using six independent parameters. They are Ground Slope, Types of Soil, Distance to Stream, Land Use & Land Cover, Settlements and Distance from Road Network because they are key factors influencing surface water pollution and their significant impacts on pollutant transport, infiltration, and accumulation according to the literature [9], [11], [16].

TABLE II. SWSI Ranges and Classes

Susceptibility Class	Very Low	Low	Moderate	High	Very High
Susceptibility Range	26-47.81	47.81-54.90	54.90-62.78	62.78-71.98	71.9-8-93

A moderate consistency is observed in the spatial comparisons of the predictive susceptibility map and the real-time observational map based on the occupancy



(a) (b)

Figure 4. (a) Surface Water Susceptibility to Pollution Map Using WLC & MCE Method (GIS) with Sample Locations (b) Water Quality Map Produced Using Sample Data and IDW

of a small percentage of the spatial area of the map by "Very High Risk" (7.38%) surface water susceptibility to pollution zones. Notably, the upper basin exhibited consistently "Very Low" susceptibility to surface water pollution. This has been found to be trending towards cooler temperatures which in turn favor the dissolved oxygen levels further boosting aquatic resilience. Moreover, the high rate of pollutant dispersion is not experienced in the river, which is attributed to the slow rate of delivering runoff due to its origin in the upper basin [26]. In upper basin, the Hydro-geomorphological features play an important role in improving the quality of water in the system due to the intrinsic ecosystem processes [31], [32]. The combination of the organic-rich mountain soils, dense vegetative cover and a well-structured terrain limits the surface runoff and helps to apply a filtration process [33], [34], whereas the presence of constant springs ensures the stable groundwater recharge. Moreover, regular precipitation will wash away pollutants on the surface, and overall decrease the banned basins vulnerability to anthropogenic pollution [35], [36].

Some large reservoirs in the middle basin that are highly susceptibility to pollution and recurrently have unfavorable water quality as seen in observed and predictive maps. This degradation has been mainly depended on the activities of other settlement areas, paddy fields and chena practices all of which result in the release of nutrients, agents of soil dislodgement and agrochemicals to proximate water bodies [37]-[39].

Although the region of lower basin including the Wilpattu national park shows relatively low susceptibility to pollution on the basis of predictive model, the water quality with regard to the existing water quality index is found deteriorated by the real water quality index map. This difference is mainly attributed to the shortcomings of Inverse Distance Weighted (IDW) interpolation method which uses the only 2 sample points with poor readings generalizing wrong conditions over the overall space. The interpolated findings upon which the report has based its suggestions are probably distorted because the conditions in the national park are quite favorable with regard to the environment: there is little urbanization, the soil is healthier as well as the pollution caused by people is minimal [40]. This underscores the need to have a higher density of sampling points to improve the level of accuracy of the assessment of water quality, especially in ecologically sensitive areas.

TABLE III. Comparison of SWSI and IDW Risk Areas Falling under Different Risk Categories (Based on developed model)

Category	**SWSI model (%)**	**IDW model (%)**
Very Low	17.42	7.95
Low	20.62	19.45
Moderate	34.92	35.78
High	19.66	30.56
Very High	7.38	6.29

According to the information provided in Table III, it is possible to identify a certain spatial distribution of surface water susceptibility emerges across the Kala

Oya basin. The lower and upper basin areas are mostly concentrated with “Low-risk” and “Very Low risk” dominating this portion and thus indicating good topography and minimal pollution effects in these areas. Comparatively, the middle basin contains a significant proportion of moderate risk zones, which most likely are associated with the high land use, agricultural runoff, and urbanization rates. Both SWSI and IDW models indicate moderate risk as the predominant category (35%), however, since IDW model is more sensitive to interpolation, the high-risk coverage is slightly higher (30.56%), thus, the overall results of the study assign Kala Oya basin as being moderately susceptible to pollution, with some focus on mitigation of this issue in the central part of the basin.

TABLE IV Sensitivity Index from to the Map Removal Sensitivity Analysis test for SWSI Map

Factor	MAD	SI
Slope	28.51	49.43
Type Soil	15.23	26.39
Distance to Roads	13.71	23.77
LULC	13.68	23.72
Distance to Settlements	12.60	21.85
Distance to Stream	11.21	19.43

Slope has the highest value (49.43) of all the variables in the model and represents the most important variable according to SI value in Table IV. The variations in slope have a direct correlation with distribution and transportation of pollutants [16].

Excessive nutrient loads in the tanks in the Kala Oya basin were observed to have caused eutrophication in most of the small and medium sized tanks identified in the previous water quality monitoring surveys conducted by the MASL in 2003 [41]. According to a Jayaratne [38] reported surface water is polluted in water quality monitoring research at the Kala Oya basin. Water quality of surface water in the Kala Oya basin thus reduces during the wet season as indicated by Athapattu *et al*.[26] and most locations have good water quality in the dry season. Although the literature has found different levels of pollution of the existing surface water in the region, the current report conducted depicts either a moderate level of susceptibility to contamination, thus identifying a precautionary point, but not of a degradation level.

IV. Conclusion & Recommendations

This study primarily aimed to map surface water susceptibility to pollution of Kala Oya basin using a geospatial model developed through six key environmental parameters: slope, land use/land cover, stream network, settlements, soil type, and major road network. With ArcGIS applications and multi-temporal datasets, this model defined the basin as a moderately susceptibility to pollution with some large agricultural reservoirs revealing themselves as highly susceptibility to pollution areas. The implications of these findings underline the demand to direct pollution mitigation action on areas where farming dominates within sub-regions, as well as replicating the overall resilience of the surface water in non-intensive areas.

The Surface Water Susceptibility Index (SWSI) simply, is capable of providing a practical and scalable approach to determining surface water quality due to the expense associated with conducting comprehensive water sampling. The SWSI model can be applied to the Kala Oya basin as well as all the other river basins present in Sri Lanka (102 in total) with an accuracy of about 80% with little dependency on the availability of large amounts of field data, which further expands its usability to a wider range of water resource management and policy formulation globally. It is suggested that, in the future, the seasonal stratification may be considered in the analysis by drawing separate water quality prediction maps during the wet and the dry seasons this may help to trace the hydrological variability better and improve the precision of the assessment of pollution susceptibility. Although the WQI of this study was developed using drinking water standards, further extensions of the current study may include inland water standards as well as enlarging the set of factors on which the SWSI model draws to increase the predictive power. These enhancements will support informed water management strategies and long-term environmental protection initiatives.

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