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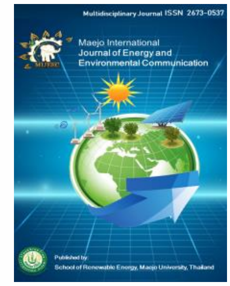

ARTICLE

Assessing nutrient budget of ungauged catchment using intermittent water quality markers

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A B S T R A C T

This study is a preliminary spatial-temporal assessment method of the ungauged catchment to determine the variation in water quality (WQ) and the land use influence on river basins' health. The intermittent WQ data, the principal component analysis, and the redundancy analysis were used to evaluate the (dis)similarity among the 10 ungauged streams and their significance in the entire catchment. These revealed some similarities/differences in nutrient pollution and latent land-use influence on the streams' health. There were similarities between R6-R7, R9-R10, among R1 to R4 basins, while R5 and R8 had distinct variances in their WQ dynamics. The intensive vegetable and rice production in R5, R7, R8, R9, and R10 basins were the major sources of high nutrient concentrations. The unique variations, especially in R5 and R8 basins could be attributed to other different pollution sources. Hence, it's of great significance to carry out comprehensive research in the above 5 river basins. That is the efficiency of management practices, identification of pollution sources, and the extent to which the elevated nutrients in the streams interact with biota within the river regime. This research offers a method to evaluate WQ dynamics in relation to human interferences in river basins of a catchment with no or limited information under similar climatic conditions.

1. Introduction

A river is influenced by watershed characteristics, defined by tributary confluences, changes in the valley and channel morphology, and or changes in riparian vegetation. These variables and natural factors, such as rainfall, temperature, weathering of rocks, and anthropogenic alterations, curtail the natural flow of the river and or alter its hydrochemistry over time (Misigo and Suzuki, 2018; Ruhela et al., 2018). Issues associated with river management are related to the complex sequence of land-use changes, water resource developments, and industrial expansion that alters the runoff pattern, river discharge quality, and the sedime-nt load transported (Dept of Water, 2015; FAO and IWMI, 2017). In the populous country such as Japan, growing human activity, and changing lifestyles, have accelerated land reclamation of the historical lagoons, mudflats, and declines in the reed cover and riparian forests, degrading the health of the rivers, estuaries, and lakeshore ecosystem (Ministry of the Environment, 2009; Gonzalez et al., 2013). River resources and their biota faces a threat from point pollution, diffuse sources of chemical used in the propagation of crops, poor water allocation within a reach that does not meet seasonal variation and riparian flow needs, and unsustainable human use of the river resource for fishing or

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recreation purposes (Santos et al., 2020; Xu et al., 2021).

Physicochemical parameters are vital to stream health due to their interaction with biota within the stream, land use, and riparian conditions. Physical parameters include flow, temperature, conductivity, suspended solids, turbidity, and color. Chemical parameters include pH, alkalinity, hardness, salinity, biochemical oxygen demand, dissolved oxygen, and total organic carbon. Other major controls on water chemistry include specific major anions and cations and nutrient species, i.e., phosphate, nitrate, nitrite, ammonia, and silica (Nweze and Eze, 2018; Hegarty et al., 2021). The physicochemical analysis does not explicitly measure the effects of concentrations of pollutants on organisms. It identifies situations where biotic communities are at risk but provides no information on the actual damage to the biota. Despite the above drawbacks, the physicochemical analysis provides vital information on the stream and forms an essential structure for rapid preassessment of the ungauged catchments.

The preservation of ecological integrity and biodiversity is prioritized to ensure sustainability. The managers must accurately assess the condition of streams and put sustainable-related policies into practice to comply with changes in water regulations. Time and resource limitations, the need for expediency, and the sheer size of the task have made 'rapid assessment' techniques a popular choice for preassessment or assessment of the ungauged watersheds. Hence, there is a need for methods that allow rapid collection, compilation, analysis, and interpretation of the results. An analysis to ease pre-guided comprehensive assessment for management decisions and actions for control and/or mitigation against pollution (Gordon et al., 2004). Thus, this study is a technique to rapidly analyze the intrinsic latent land use dynamics influencing variations in the WQ of a catchment with no historical dataset. The technique provides a rapid preview of rivers' health and paves a way for a prioritized follow-up or extensive surgery on specific river water resources.

2. Materials and Methods

2.1 Study area

Isahaya Reservoir catchment is approximately 248.67 km2 encompassing 10 river basins. The rivers stretch from 1100 meters above sea level and fall into a plain (5 meters below sea level), mainly farmlands, before discharge into a regulated Isahaya reservoir. According to Ota, over 266 km2 of mudflats were reclaimed for farming with the inception of the regulating reservoir in 1997(Ota, 2018). The main land use is forest covering approximately 61.6% mainly on the steep slopes, and Farmlands 32% within the plans with isolated orchards and terrace rice on gentle hills slopes. This region experiences temperate-type climatic conditions with dry winter and semi-humid rainy summer seasons. The average annual temperature in Isahaya is 16.3 °C. Annually, the temperature typically ranges from 3°C to 31°C and is rarely below -1°C or above 34°C. June to July are the wettest months, besides precipitation of about 350.0 mm, and December to January are the driest months, with total precipitation of about 65.0 mm. Isahaya region experiences annual total precipitation of 1800 - 2200 mm.

2.2 Data acquisition

To evaluate the spatial influence of various land use in specific river basins and variations within the catchment, the Soil and Water Assessment Tool (SWAT) was utilized. Table 1 contains various data sets that were utilized as input conditions for modeling and predicting the loading at ungauged discharge points (10 rivers). Due to insufficient hydrological data, the single gauge flow information upstream of R6 was transplanted to discharge points of the 10 rivers according to (Misigo, *et al*.,2022). Nutrient markers at the discharge points were determined by sampling and undertaking chemical analysis throughout a year cycle (all four seasons). Actual crop management within the Isahaya region was informed from the Kyushu region/Nagasaki Prefectural reports, and related research work. The information encompassed the land preparation period, types of crops, fertilization regimes, crop/land management operations, harvesting, and post-harvest operations (Myint *et al.,* 2010; Nishida, 2011; Li *et al.,* 2016).

Table 1 Types, sources, and description of the data acquired

Data type	Scale	Source	Description
Digital Elevation Map -TIF	Resolution 10 m x 10 m	USGS Earth explorer	Elevation, slope, channel lengths
Soils – TIF	Japan 1:50,000	Japanese soil inventory National Agriculture and Food Research Organization (NARO)	2017 Version
Land Use – TIF	10 m resolution	Jaxa, Japan	2018-2020 version
River Discharge – CSV	Use of a framework to transplant flow information from gauged to ungauged sites	A method for estimating flow at ungauged site (Misigo, *et al.*,2022)	Daily mean flow at discharge point for Aug. 2020- Jul. 2021
Water Quality Analysis	Sediments and nutrients concentration mg/L	Sampled and analyzed in the laboratory. Use of spectrophotometric method (nutrients)	April 2020 -July 2021

TIF – Tag Image File Format and CSV - A comma-separated values

2.3 The catchment nutrient budget

2.3.1 Spatial-temporal variation of the water quality across the watershed

With an intent to understand the WQ dynamics of the watershed, the intermittent observed data and the mean daily loadings simulated were analyzed. The data were interrogated statistically considering the:

a. Variation and similarity in water quality across the river basins.

b. Land use dynamics and the role in the nutrient concentration or loadings.

c. The significance of each river basin regarding the mass movement of materials downstream.

To extract the above information, the following multivariant statistical techniques were utilized.

i. Principal component analysis (PCA)

PCA is a robust dimensionality reduction technique for exploratory data analysis/visualization. It is a linear transform that reduces a considerable dataset size, minimizing any loss of information to understand better and interpret the data's structure. It preserves as much of the 'variance' or 'spread' of the data in a lower-dimension space as possible (Jollife & Cadima, 2016). In determining the principal components, the eigenvectors and eigenvalues of the data covariance matrix are calculated. This results in an axis system in which the covariance matrix is diagonal. The eigenvector with the largest eigenvalue is the direction of most significant variation denoted as the first PC. The second PC has the second largest eigenvalue in the (orthogonal) direction with the next highest variation, and so on. This extracts the vital information from a vast dataset and represents it as a set of new orthogonal variables called principal components. The principle components display the pattern of similarity in the samples and variables as points in maps (Abdi and Williams, 2010).

ii. Redundancy analysis (RDA).

Finding patterns in the scatter of data points that are maximally and linearly connected to a group of limiting (explanatory) factors is done using an expanded version of PCA with constraints. It is a gradient analysis method that was used to condense linear correlations between response variable components (i.e., 6-WQ variables) with a set of explanatory variables (i.e., land uses). It explains the variation in a set of response variables constrained by the second set of predictor variables. It links multivariant multiple regression and PCA (Borcard et al., 2011).

2.3.2 Use of intermittent observed data as markers in predicting nutrients loads

To evaluate the importance of each stream in the catchment and receiving water body, interpolation using a hydrological SWAT (Soil and Water Assessment Tool) model was applied. However, there was only a single flow gauge in the whole catchment. Thus, calibrating and validating the model was untenable to transfer parameters' value ranges from the donor either by averaging or regression (Hrachowitz et al., 2013; Poissant et al., 2017). Therefore, the flow characteristics of the ungauged rivers were estimated by transplanting flow signatures using the new framework (Misigo *et al.*, 2022). The flow signatures were then applied to determine each river basin's seasonal nutrient loading. There were no WQ data for the 10 streams in the catchment despite the water quality issues exhibited in the receiving Isahaya reservoir and subsequent Ariake sea (Luo et al., 2011; Ota, 2018). Using intermittent data collected for 1 year, the SWAT model was calibrated and validated for each nutrient at a time. The nutrient parameters included: sediments (Sed) in tons, orthophosphate (PO_4^{-3}), total phosphorous (TP), nitrate (NO_3^-), and total nitrogen (TN) in kilograms(kg). The following objective functions were utilized to optimize prediction and evaluate model performance*: Nash–Sutcliffe model efficiency coefficient, Pearson Coefficient of Correlation, and Modified coefficient of determination.

3. Results and discussion

3.1 Nutrients dynamics in Isahaya Reservoir catchment

a. Sediment's dynamics in relation to other variables

There was a strong positive correlation between the concentrations of TSS and TP in R3, R5, R7, and R10 basins with a coefficient >0.65. R1, R4, R8, and R9 basins showed a moderate positive correlation between the TSS and the TP, while R2 and R6 basins showed a low positive correlation. R1, R7, R9, and R10 showed a moderate association between the TSS and PO4 (coefficient of $0.57 \leq 0.61$). The other rivers (i.e., R2, R3, R4, R5, R6, and R8) had a weak association of a positive correlation of less than 0.5. Only R3 showed a strong positive relationship between TSS and TN concentration. Figure 1 except for the relationships between the TSS concentrations and the TP.

The in-channel fluctuation of the TSS and nutrient concentration in an individual stream is governed by abiotic and biotic processes relative to changing flow conditions (Haggard and Sharpley, 2006). n R1, R7, R9, and R10 basins, the transport of TP positively correlated with the mass movement of sediments. Also exhibited by an elevated TP concentration due to the retention of sediments during base flow (Fig. 1.). During episodic storm events, results showed an increase in both sediment and phosphorous concentrations. R3 basin showed stable concentrations of TSS and TP throughout the observation period with a single peak. R5 showed random fluctuating of both TSS and TP that strongly correlated. The general increase in flow due to changes in seasons showed an increase in the concentration of TSS and TP for R1, R7, R9, and R10 basins.

The R2 and R8 basins showed random fluctuation in TSS concentration throughout the year with no apparent pattern.

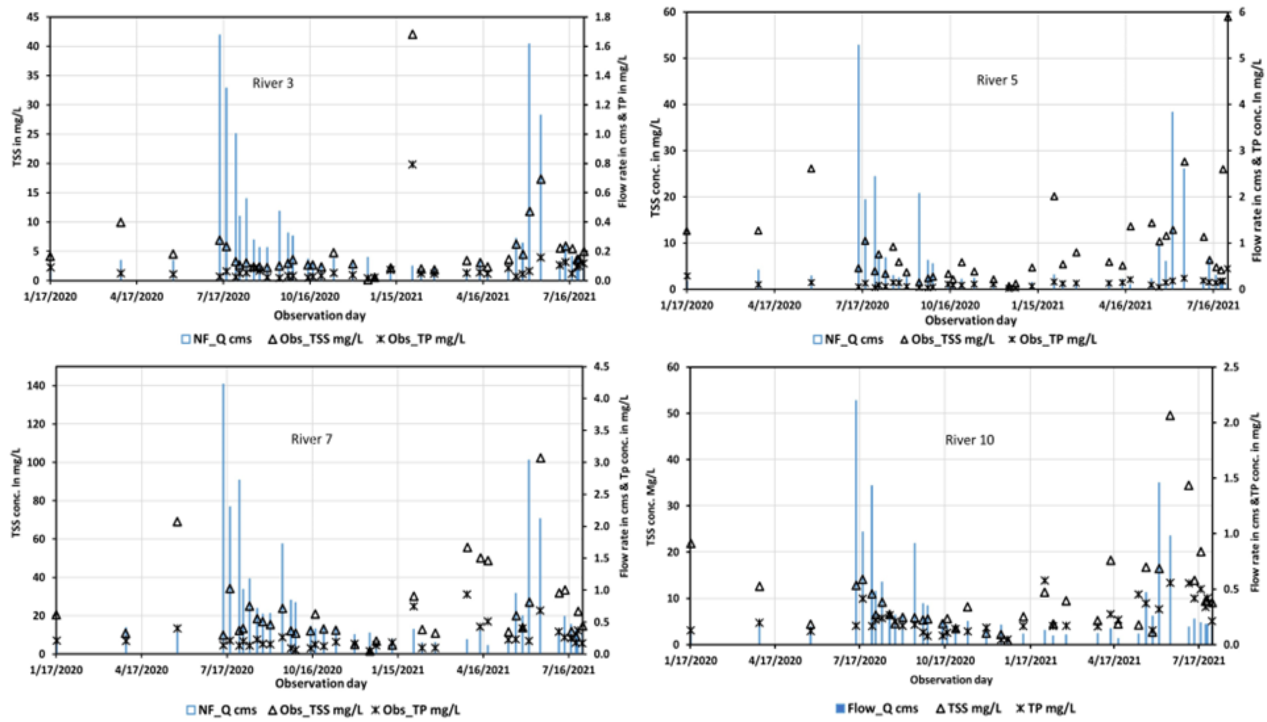

Figure 1 The changes in total suspended solids and total phosphorous concentration

There was variation in TSS concentration for the R6 basin during base flow, but it remained elevated during high flows. R2, R4, R6, and R8 basins had a stable phosphorous concentration during baseflow conditions with a slight increase during the onset of the rainy/cropping season, but due to the inflow and dilution effect stabilized. The changes indicated the retention of sediments and nutrients during baseflow and resuspension of material within the stream as well as the other washed matter by runoff from the catchment. Thus, the size of the increment depended on the weather and activities in the catchment.

b. (Di) Similarities in the river basins

The R10 basin was strongly associated with changes in water quality of R1, R3, and R4 basins (6 variables R> 0.5) and moderately related to R7 and R9 basins (5 variables R> 0.5). The R4 basin was strongly associated with R3 and R5 basins and moderately associated with R1 and R2 basins. R2 basin was strongly associated with the R3 basin and moderately associated with the R1 basin. The R8 basin was moderately associated with R7, while the R1 basin was moderately associated with R3. Therefore, it was deduced that R6, R8, R9, R7, and R5 were unique from each other with minimal association with other streams.

Principal component analysis (PCA) was undertaken to identify patterns in a data set/structure and then distill the variables down to their most essential features to simplify the data without losing important traits (extracting meaningful signals from the noise). Of the six factors, two major factors had characteristic values >1, i.e., PC1, and PC2, which explained cumulatively 73.44% of variations in the WQ data.

The data were reduced into a two-dimensional distribution factor plot explaining the variation in WQ at each sampling site, as seen in Figure 2. TP, PO4, and TN had the highest loadings along the PC1, accounting for 55.4% variation in the WQ data. Table 3 shows phosphorous had the greatest loading extent of 49.2% TP and 46.6% PO_4. Nitrogen had the second-highest loading variation of 46.6% TN and 38.7% NO_3-N. The second factor (PC2) was composed mainly of NH_4^-N and NO_3-N. TSS correlated with PO_4 and TP, while TN was associated with NO_3-. R1, R2, and R4 exhibited close association with R3 along PC1. The high loadings of NH4-N influenced the variability of R5 from other streams compared to other streams. The similarity of R6 and R7 was much driven by NH4, TSS, and PO_4 concentrations. High nutrient variability brought out R8 as a unique river influenced mainly by nitrogen (TN & NO_3) and moderately by phosphorous (TP & PO_4) loading. R9 showed a positive association in nutrient variability with R10 influenced by TSS, nitrogen, and phosphorus.

c. Land-use influence on the nutrient load in the catchment (using RDA)

Constraining the sampled WQ with differences in land use per stream, the RDA results showed that intensive farming of vegetables (AGRC) throughout the warm season is one of the significant determinants of WQ variation in the Isahaya catchment (Figure 3). Both phosphorous and nitrogen concentrations were primarily driven by vegetable farming in the region. Variation in TSS concentration in the catchment had the most extensive loading, with rice fields being the major source. Wetland preparation, sediment-rich irrigation water returned to the stream and poor management practices contributed to elevated sediment in the streams. High-density urban regions seemed to have minimal impact on variation in WQ. Urban dynamics had the most influence on TSS and the least on changes in NH_4. All the WQ parameters were negatively associated with forest cover in the catchment.

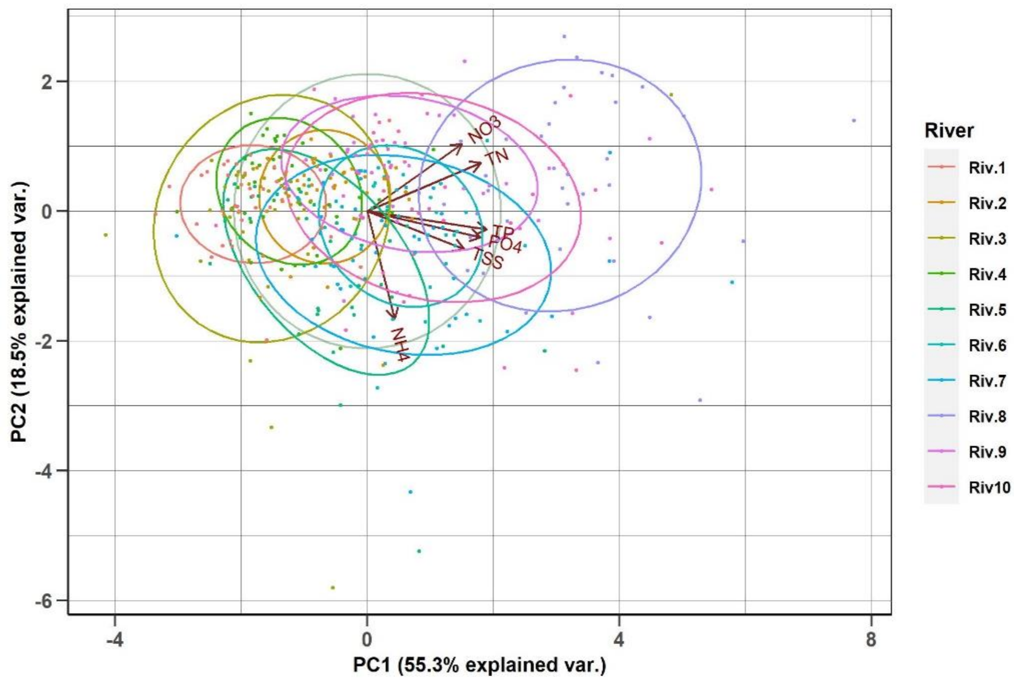

Figure 2 PCA biplot with river grouping: 390 samples were plotted along PC1 and PC2 and grouped by nutrients. PC1 explains 55.4% of the total variance in the data

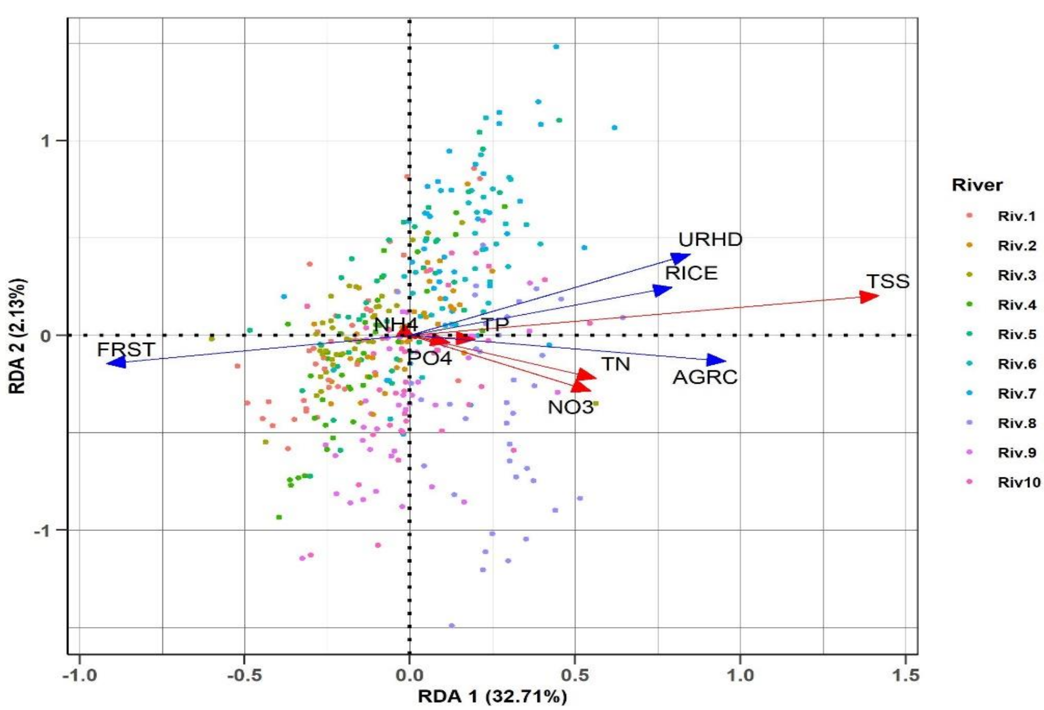

Fig. 3. Redundancy analysis of WQ characteristics constrained by land use activities. WQ is indicated by red arrows and land use activities indicated by blue arrows.

The implementation of both PCA and RDA revealed some disparity in the WQ observed. For example, the R5 basin showed a high concentration of NH4 despite having the second-lowest portion of the watershed under AGRC land use. It strongly indicates that point source discharge might influence the high concentrations other than the effects of cropping in the river basin. It explains the bad odor experienced during field observation. It is the resultant ammonia from ammonium with changes in temperature and pH (Huff, 2013; USEPA, 2013; Martin, 2014)). R7 had the highest TSS concentration, especially during rice planting season. Despite the R8 basin having nearly the same portion of the catchment under rice production as R7, the low TSS in this basin is largely explained by the differences in slope and best management practices. Most of the downstream of R7 is an open rice field, whereas on R8 there are strips of uncultivated land and vegetation along riverbanks that form filters (Jaspers-Focks and Algera, 2006) during surface flow. The movement of the sediments from R7 explains the peaks in phosphorous concentration during rainfall events.

The warm season intensive vegetable production (AGRC) within R8 (i.e., 28.25% of the river basin) is the largest in the entire catchment. High concentrations of nitrogen in the stream were partly explained by the fact that heavy fertilization is used for production (organic and inorganic fertilizers incorporated in the soil or applied on the surface as a top dressing or sprayed on the crops). Due to the reduction of runoff and the baseflow dynamics (Shore et al., 2017) during the dry cold season, the concentration of nutrients is poised to rise significantly. The elevated nitrogen variation within this river needs further investigation to establish whether there are other sources or if BMP effectively ensures that fewer nutrients from the farm find their way into the streams. R9 had a more extensive forest cover than R10, though an equal portion of the land is under AGRC.

By proximity, the two rivers have a strong association with variations in phosphorous and nitrogen concentrations. The high concentration in these rivers was not apparent, thus requiring further investigation for both BMP and other possible sources from the activities in the river basin, e.g., animal farms.

3.3 Seasonal loading

The intermittent WQ data were divided into two seasons: wet and dry season samples, since data collected covered only one complete season. Considering the sequence of observed data, the first half of every season's data were used as markers to calibrate the SWAT model. The model could depict the seasonal loading in the river basins for the 5-WQ variables considered in the study. The bR^2 of ≥ 0.4 was accepted for this research if the other two objective functions were over 0.5. Few sites recorded $bR^2 \geq 0.4 \leq 0.5$ but high values of NSE and R2 since bR2 considers the similarity in trend and the magnitude of the two signals being compared (Sao et al., 2020). The lowest prediction was recorded for sediment output at the R7 basin. This could be explained by the high slope, large rice cultivation, and evident poor management practices. Despite the difference in the catchment area to R8, the R7 yield of sediment during peaks equals R8's loading (Figure 4). R3 and R5 showed the least sediment yield given the minor agricultural activities and the presence of proper management practices (vegetation strip separating the riverbank and the farms). R8 showed stable loading throughout the year (with the least difference in peak and lowest loading). The peak sediment load was noted during the wet summer season and the most negligible loading was during the onset of winter after the drier autumn.

The TP loading in the catchment followed the rainfall and sediment loading trends. The R6 showed high peaks during the wet season, with the lowest loading at the least baseflow (dry season). R8 TP load in response to precipitation was not as sensitive as R6 but showed the highest loading during the dry season compared with the other 9 streams. On the other hand, R7 and R8 showed a higher response in TP load to rainfall events than R6, as represented in Figure 5.

R8, R7, and R1 basins also showed a high response in TN load as compared to R9 and R6 during rainfall events, as shown in Fig. 6. Fig. 7, shows the distribution of various nutrients load transported by the 10 rivers in the Isahaya catchment. Apart from the major stream (R6), the other rivers could not be ignored for managing the water quality in the receiving reservoir. The substantial load they discharge into the reservoir would play a huge role in ecological stability and sustainability. Land use and management practices within the river basin directly or indirectly determine the stream's health and ecosystem sustainability. Apart from using fertilizers from intensive vegetable and rice production, there seem to be other contributors to poor WQ, especially for R5, R8, R9, and R10. The effluent from animal farms, wastewater from greenhouse farming, and the treated domestic effluent from apartments (with localized pre-treatment systems) need in-depth analysis to determine their role in the health of the streams.

The impact of organic manure (i.e., wheat straw or rice straw mixed with cattle/swine) incorporated into paddy fields/vegetable production farms on a stream nutrient concentration should also be evaluated. As reported by Nishida (Nishida, 2011), such composing manure have a relatively similar supply of nutrients to inorganic fertilizer. Organic manure's high nutrient retention, ease of transport through runoff, poor incorporation into the soil, and poor irrigation management practices contribute to nutrient pollution and the turbidity of stream water. In comprehensive follow-up research, the streams with large areas under rice and warm-season intensive vegetable farming (R2, R6, R7, R8, R10) should be targeted sites in evaluating the role of organic and inorganic fertilizers used in the river basin and any possible point source. Despite R5 and R9 basins having over 70% of the total land under forest, the poor WQ needs a further appraisal to determine the dynamics leading to elevated nutrient concentrations in the streams. The high NH4-N in R5 compared with other river basins with a large area under agricultural production is a clear indicator of other sources of pollution that should be identified and mitigated against.

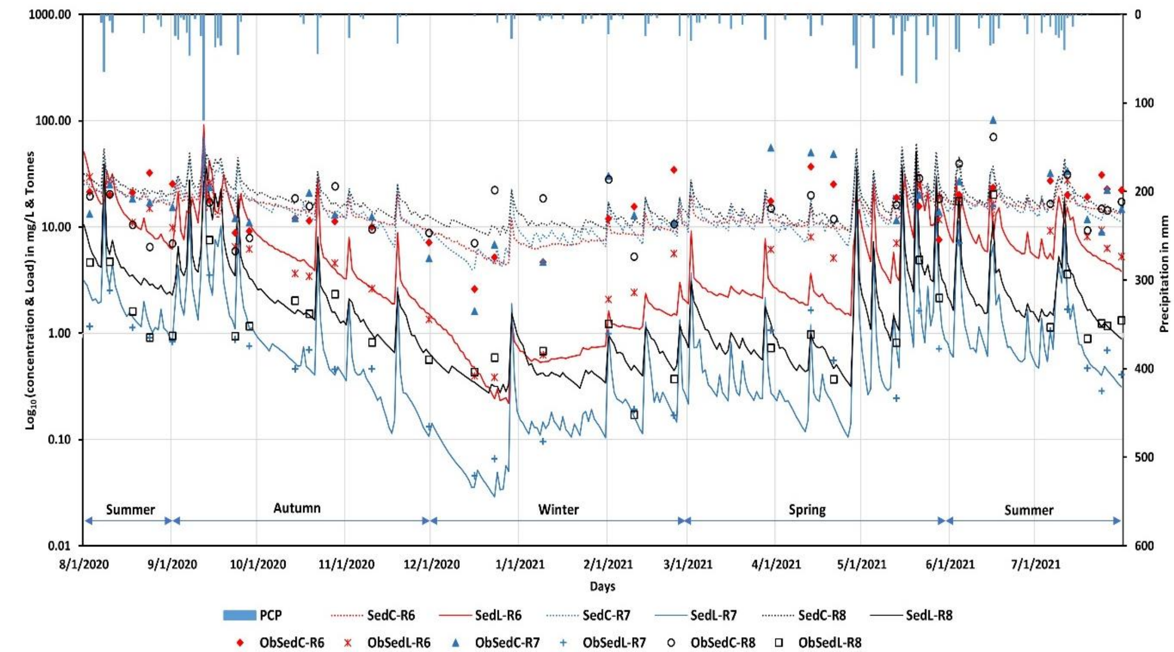

Figure 4 The seasonal sediment dynamics for the 3 major streams in the ungauged catchment (ObSedC/SedC and ObSedL/SedL observed/Simulated sediment concentration and load, respectively)

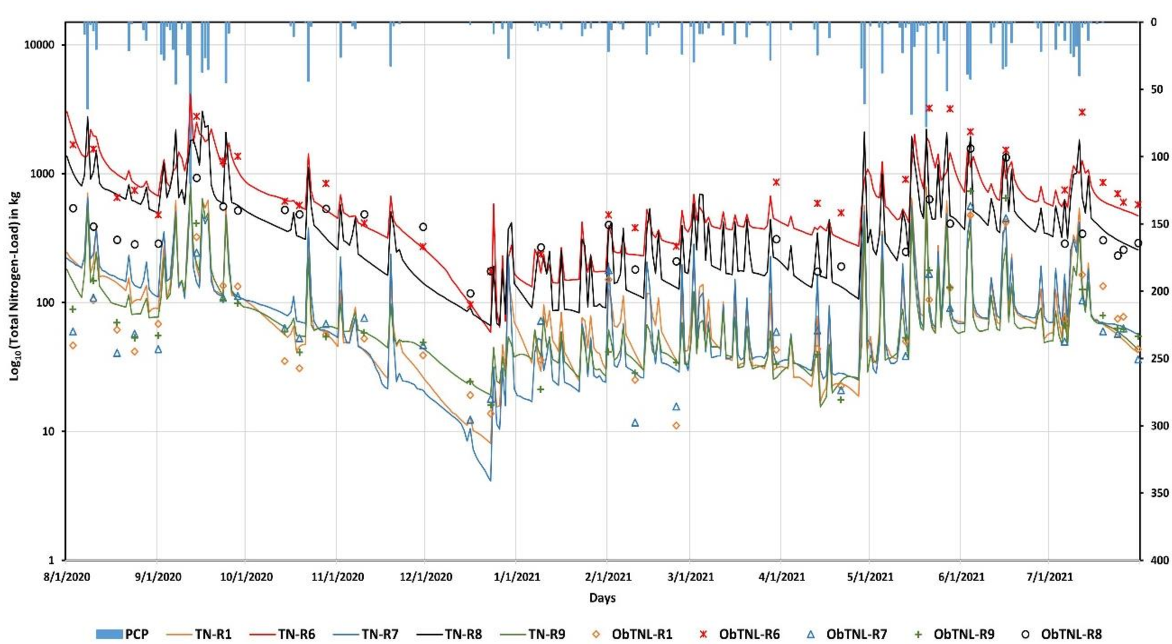

Figure 6 The seasonal TN dynamics for the 4 streams in Isahaya catchment (ObTNL-observed and TNL-simulated TN-loading)

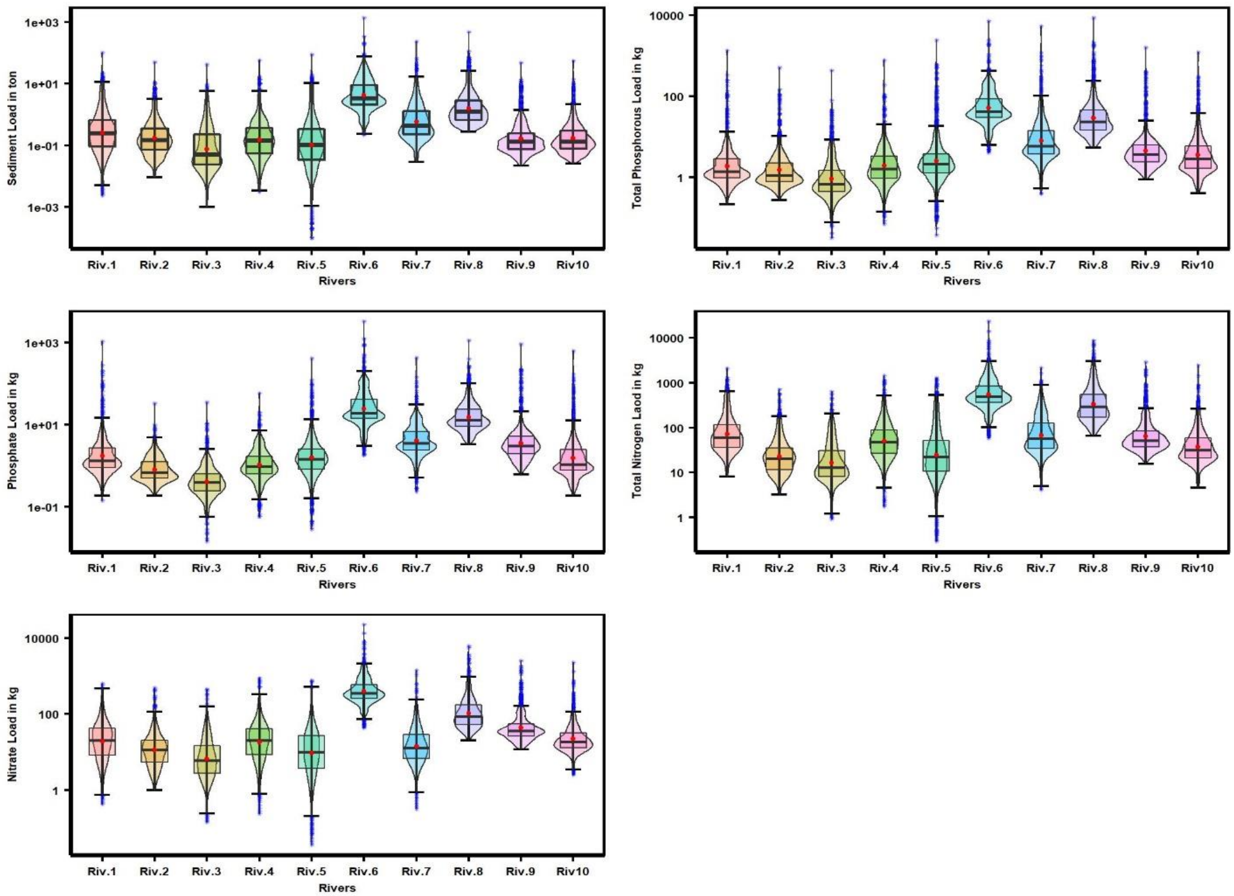

Figure 7 An estimation of nutrient loading in the entire Isahaya reservoir catchment

3.5 Uncertainties

The uncertainties in defining seasonal concentrations and loadings at each of the ten discharge sites hinted at possible errors in transferring flow data from ten river basins from a single gauge (donor), the assumption of similar weather conditions throughout the catchment, and the lack of continuous data at each site. An estimation range of variables was considered for the flow accounting for possible input, calibration, and validation errors. Quality control measures were applied during collection, treatment, and storage to minimize errors. Measurement errors during chemical analysis depended on the equipment or method used. Analysis was always done in replicates and averaged to minimize errors. The most considerable variation of less than ±8% was recorded during digestion for the estimation of TN and TP, while the least variation of less than ±4% was recorded during the determination of PO4-P, NO3-N, and NH4-N. To effectively use the data or information from this work for further study, analysis, or comparison, the above uncertainties should be incorporated for decision-making.

4. Conclusion

Water managers are required to effectively appraise the health of streams and implement sustainable policies that emphasize on protection of ecological integrity and biodiversity. Due to time and resource limitations, there is a need for a rapid assessment technique for preassessment or assessment of the watersheds. Rapid preassessment can provide information for making management decisions and actions for controlling and/or mitigating pollution. Such preassessment information can also ease a follow-up comprehensive assessment. Unconstrained principal component analysis (PCA) was applied to evaluate the variation in WQ at the discharge points. The PCA results showed the similarity of WQ at R1 to R4, R6 - R7, and R9 - R10. There was a distinct variance at R5 and R8 discharge points influenced by different factors. The redundancy analysis (RDA) evaluated the impact of land use on the WQ. The PCA and RDA identified the important WQ parameters at each site, revealing differences in nutrient pollution and latent factors that influence the streams' health. Intermittent data to estimate the loading at each site revealed seasonal dynamics at the 10 sites. The simulation showed the variation at each site and the importance of each basin in the entire catchment. While this study does not offer an exclusive technique for rapid evaluation of a catchment, it provides a guideline that could be applied to estimate and characterize seasonal variation in water quality for a catchment with limited data. Rapid evaluation can provide grounds for decision-making or pre-guided comprehensive research of ungauged catchment.

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