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SENSITIVITY ANALYSIS OF A PREDICTED POLLUTANTS MODEL FOR KANGIMI DAM STORAGE

ABDULKAREEM[1], I. A., D. MOHAMMED[1], M. T. MUSA[1], S. H. ABDULRAHMAN[2]

[1]Department of Agricultural & Bio Environmental Engineering, Kaduna Polytechnic, Kaduna

[2]Department of Agricultural & Bio Environmental Engineering, National Water Resources Institute, Kaduna

aibrahimayinla@gmail.com

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Reservoir,
Sensitivity Analysis,
Streamflow

Abstract

Sensitivity analysis (SA) has been widely accepted and used in sourcing and explaining hidden questions arose from mathematical models. This study aimed at use SA on an existing recently predicted pollutant model for Kangimi Dam Storage. The study calibrated and simulated the model using primary and secondary stream stage data. The SA was performed using five (5) different methods and evaluated the results by comparisons. The simulation indicated that the pollutants responded to the seasonal changes of reservoir streamflow and reached the optimum at month of August. The pollutants at months of June, July and August (2023) [redacted] substantially showed a significant sensitive to streamflow discharges as it become optimal. And in conclusion, the study predicted the chemostatic and chemodynamic patterns of the reservoir storage, and recommend the further study of the SA on the model for its further verification and acceptance.

Introduction

Sensitivity analysis (SA) has been widely used in examining mathematical models which greatly depending on the purpose or task in solving problems that ranged from the test of robustness of the results from a model or system, the understanding of the relationships between outputs and inputs, in

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reducing the uncertainty to provide the most significant inputs, detect errors in a model or system in defining unexpected relationships between outputs, inputs and simplify a model in removing inputs that do not have a strong influence on outputs, and make a model accessible for interpretation for understandable explanation to inputs according to Sysoev (2023).

Some of these techniques proposed for sensitivity analysis have been on universal level or applied for a model that has a predefined structure. Most importantly, sensitivity analysis is generally divided into two groups namely local and global sensitivity analysis according to Saltelli (2008). The approach to local sensitivity is based on obtaining a tendency about the uncertainty of the output with the respect to a change in one or more of its inputs and has been described to have delivered accurate and adequate results (Sysoev, 2023). On the global approach, it suggests delivering results taking into account the changes to not only one factor but to all factors to consider possible interactions between them.

Among the areas where SA has been used are environmental field, water resources, economic science, engineering, medicine and several others. In the area of water resources Saminu *et al* (2015) used SA on the Optinetwork software for water distribution system, Sysoev (2023) proposed alternative approach based on applying analysis of finite fluctuations that uses the Lagrange mean value theorem to estimate the contribution of changes to the variables of a function to the output change. Therefore, the study aimed at use SA on the recently formulated model to test the predictive ability and reliability for understanding of interpretation of seasonal reactions on the reservoir storage.

Methods and Materials

Description of Model Concept and Method

Formulating a model to predict a system of water pollution quality is a complex task, nevertheless, it has always been based on assumptions on the basis of the concept focus of the modeler. Predicting the concentration of contaminants which are stable in nature does not pose much challenge since their concentration changes only due to mixing/dilution or effects brought by precipitation, evaporation, sedimentation, adsorption or chemical reactions with other substances (Abdulkareem *et al.,* 2023). The reactions that may be influenced by the factors of sun, channel bed characteristics, pH, temperature, and many others of which they must be considered separately for respective substance mixtures and local conditions.

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Water body received pollutants from point source or non-point source. The point source defines the pollutants entering the water body from a well-defined outlet or locations such as municipal or industrial waste. While the non-point source is a key feature of surface-water from the river/stream catchment or watershed, which is delineated by topographic, drainage, and all surface runoff within the catchment or watershed that have the potential to flow into the river/stream body. This kind of pollutants are associated to sediments, or originated from non-point source that have interplayed with climate, soil properties, land use, vegetation, human activities, and streamflow characteristics (Abdulkareem *et al.*, 2023).

The model in question is on the concept of non-point loads of which it was considered enough to say that the physical, biological and chemical characteristics of water contaminants from the watershed to the reservoir storage is linearly related to catchment discharge (pollutants) on the basis of homogeneous assumption with multiple pollutants' constituent concentrations exists in the surface runoff. Hence, the related equation was given by Abdulkareem *et al* (2023) as

$$P_w(t) = C_1(t) + C_2(t) + C_2(t) + \cdots + C_n(t) \quad (1)$$

In which $P_w(t)$ defined the water pollution quality (pollutants) concentration, *mg/l* in a period of time and C_{1-n} the concentration of each number of pollutants in water, *mg/l* in a period of time.

However, equation (1) then formulated based on the assumption that there is seasonal flow through homogeneous catchment; pollutants flow through agricultural and land uses; pollutants are contained in litres of water which is directly proportional to the time period of the year; and considered when an element concentration is found higher than acceptable or permissible limit of NIS (2015) and WHO (2004). By these assumptions, pollutant loadings into the reservoir storage are strongly controlled and directly proportional to the inflow discharge, *Q* from the catchment empirically represented by the point slope equation of a straight line

$$C_P = aQ + b \quad (2)$$

Q is the streamflow discharge, m^3, a and *b*, are the intercept and slope gradient, respectively.

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The model which developed using logarithmic transformation has the streamflow discharge independent variable and pollutant constituents' concentration, the dependent variable. The solution was sought using logarithmic transformation

$$Log\ P_w(t) = LogC_1(t) + LogC_2(t) + LogC_2(t) + \cdots + LogC_n(t) \quad (3)$$

The model by Abdulkareem *et al* (2023) was given by

$$Log(P_w) = Log(558.58) + 0.119LogQ_t + 0.229LogQ_{tds} - 0.173LogQ_{cl} + 0.066LogQ_{NO} + 0.128LogQ_{bod} \quad (4)$$

From equation (4), the 2nd term to 6th term represents the power model of turbidity, total dissolved solid (TDS), Nitrate (NO_3) and Bio-Oxygen Demands (BOD) concentration, respectively.

Data Acquisition and Processing

The acquisition of data for processing simulation are in three (3) folds. (i). The representative water samples from the reservoir storage for the months of April, May, June, July, August and September 2023 representing raining months, (ii). Correspondents and simultaneous observed, measured and recorded reservoir stages, and (iii). Secondary data of average daily reservoir stages (m) of April to September of 1993 to 2022 as recorded at Kangimi Dam Gauging station mounted and managed by Kaduna State Water Board. The study heavily relied on the both primary and secondary data of water agency (KSWB) due to applauded accuracy given to the discharge data obtained from permanent gauging station on a stretch of a river or reservoir according to Kuusisto (1996) which established stable relationship between stage and discharge. The primary stage data were compared (measured) with secondary stage data of same gauge of 1993 – 2012 to check for outlier values, measurement reliability and, to avoid exceeding or under recording the stage values. Meanwhile, the data were subjected to statistical analysis for data assurance and reliabilities.

The correcting gauge-height values were processed using Natural Geodetic Vertical Datum (NGVD) (World Meteorological Organization (WMO), 1980). The datum adjustment constant of 579.12m obtained by KSWB (1977) produced dam height at various storage volumes.

A rating table of Kangimi dam produced by National Water Resources Institute (NWRI) (2012) was obtained and plotted on Microsoft Excel Spreadsheet (2016) to produced exponential best of fits. The rating curve has been described to be crucial because it allowed the use of stream stage to determine and

estimate the corresponding streamflow according to Andrews (2010). The annual storage discharge for various stages was then generated from the exponential model which help to estimate streamflow discharges equivalent to the measured and recorded stages for the months of April – September, 2023.

Model Calibration and Simulation

Calibration of the model was done using the acquired primary and secondary stage data from the reservoir. The sensitivity analysis was measured using five (5) acceptable methods:

i. Pollutant simulation using streamflow discharge versus pollutant concentration, has been adjoined to be a good strength according to Porter (2020) study. Herndon *et al*. (2015) and Zimmer *et al*. (2019) defined the concentration export patterns to be chemostatic if -0.1 ≤ b ≤ 0.1, that translated to pollutant concentration varied little with changes in streamflow discharge, while chemodynamic defined b > 0.1 also concentration varied significantly with stream discharge. de Mesquita Lopes *et al.* (2013) defined the values grade at low when the value is 15.9%, medium at 68.3%, 13.6% and 2.3% high and very high, respectively.

ii. The strength relationship is measured by the coefficient of determination (R^2) which measures how much of variation in solute concentration is explained by variation in streamflow discharge. On other hands, Thompson *et al*. (2011) equation was used to provide a more robust assessment of what is occurring in the catchment into the storage by calculating the coefficient of variation (*CV*) of the solute concentrations and dividing it by the coefficient of variation of stream discharge which measures the degree of chemostatic vs chemodynamic. Chemostatic behavior is indication of greater variability in the solute concentrations, translated that streamflow discharge is not the sole factor influencing concentrations.

iii. Another approach for sensitivity measurement as described by Sysoev (2023) based on the analysis of linear models if there is an available set of inputs and outputs, and possible to fit the existing relationship linearly is the commonly used indices, partial correlation coefficient (PCC) defined

$$PCC = \rho(x_j - \hat{x}_j, y - \hat{y}_j) \quad (5)$$

The conclusion is drawn If $\rho(x_j, y)$ is –1 or 1, describing that the system output is dependent on the tested input value indicating the output is connected linearly. Also, if every set of (x_j) and (y) are not connected, the correlation coefficient is 0. PCC is the degree to which y is affected by x_j when the effects of the other inputs have been nullified.

iv. The percentage effects and sensitivities of predicted pollutant concentrations at every month in the reservoir storage streamflow in the advent of runoff and direct rainfall contribution was performed on Microsoft Excel 2016. The tool is very robust and visually indicated the percentage of contributions and monthly sensitivity of reservoir storage to pollutant concentrations in the available water.

v. Further study was focused on statistical trends analysis to identify if the values of the variable is generally increase or decrease over some period of time, because the trends in hydro data series (streamflow) has been ascribed to variability according to Ayinla *et al.* (2021), and buttressed by von Bromssen *et al.* (2022) that trends should be observed in addition to relationship between concentration and streamflow when such trends could influence the accuracy of slope estimation. For the model, estimation of the trend magnitudes and statistical significance of the average monthly streamflow for every pollutant using the power model is equal to slope of the line, *b*. This concept framework was supported by Maher (2011) and simply interpreted as change from increase (+ve) to decreased (-ve).

Results and Discussion

Simulation and Sensitivity Analysis

The optimum predicted pollutant concentration is presented in Figure 1, and described the simulation of the monthly pollutants in Kangimi storage for the period of April to September, where the monthly average change rate is presented in Table 1.

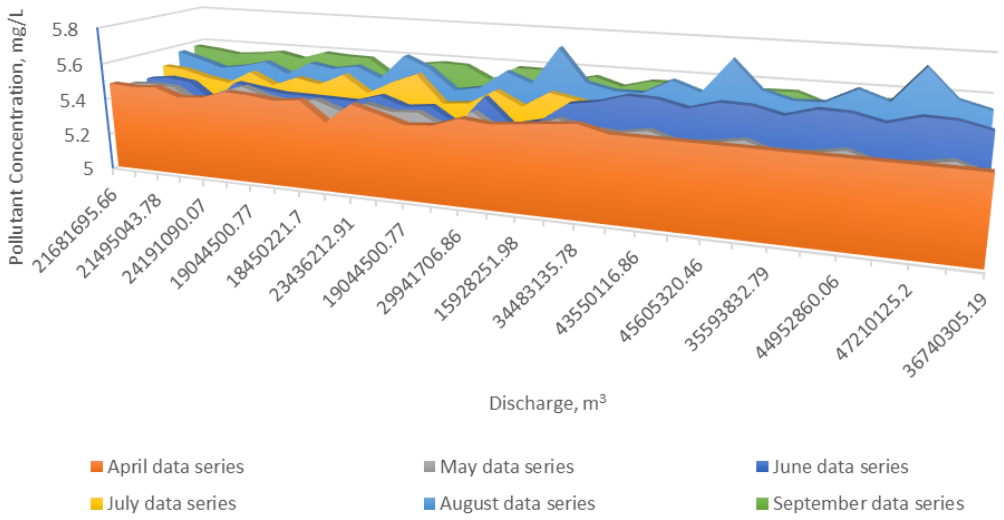


Figure 1: Simulated monthly Pollutant concentrations

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Table 1: Pollutant monthly response change

Month	Change	Statistical Mean (mg/l)
April	-0.002	5.45
May	-0.003	5.42
June	0.0085	5.49
July	0.0048	5.48
August	0.0059	5.56
September	-0.002	5.55

The simulation in Figure 1 provides the dynamics and trends insights into storm event for the months of April to September pollutants concentration in Kangimi reservoir storage. This revealed that the reservoir system responded to the seasonal event as pollutant concentrations responded to streamflow discharge with variability. The resulting patterns and magnitudes of responses of the pollutant concentrations of the considered months (April – September) at the beginning revealed enrichment patterns which suggests surface inflows contribution for every month with mixed actions.

The pollutant-streamflow patterns for the months of April and May as shown in Figure 1 exhibited slight dilution at the beginning and subsequently flat towards the end. This revealed that the factor of initial streamflow storage controlled the pollutant concentration as the pattern approaches flat and could also be explained that it is sensitive to available streamflow when little or no runoff inflows from the catchment source. In another hand, the slope of the curve suggests the average rate of change where positive slope shows enrichment pattern and negative slope showed dilution pattern according to Chen *et al* (2020), and therefore, the slope obtained in Table 1 confirmed dilution pattern. The significant information here is that streamflow control pollutant concentration and remained constant as curve remained flat for the months April and May.

The positive changes (slopes) of June, July, and August with values of 0.0085, 0.0048 and 0.0059, respectively in Table 1, satisfied the enrichment patterns condition as described by Chen *et al* (2020), though with weak enrichment patterns. The range statistics mean values of the concentration remained higher (5.48 – 5.56 mg/l) than any other months of same raining period which indicated enrichment and dilution period.

The months of June and August showed a substantive sensitivity to streamflow discharges as pollutant concentration become optimal (Figure 1) probably

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suggested the persistence surface inflows, direct rainfall contribution and completion of mixing and flushing in the storage. Furthermore, Figure 1 showed the month of September sensitive to change from the month August (positive) to negative, the process Chen *et al* (2020) described to be the occurrent of dilution pattern and flushing of pollutant concentrations in the stream storage water. The result suggests the pollutant concentration has completely reached the maximum value of mixing, flushing, dilution, neutralization and enrichment processes. Therefore, it can be relied upon to say pollutant concentrations during this season (2023) does little effects in general reaction condition of the Kangimi dam reservoir as range of concentration of the pollutants still remained 5.42 – 5.56 mg/l (Table 1) at the peak of raining season of the Kangimi watershed.

The overall agreement of model with simulated data gave a baseline value of 1.0 by using partial correlation coefficient (PCC) valuation. This shows that the system output is a dependent of the existing input (streamflow), and the output is connected in a linear manner.

The model predicted pollutants percentage saturated level is presented in Figure 2. The result further defines the percentage effects and sensitivities of predicted pollutant concentrations for every month in the reservoir storage streamflow as runoff and rainfall contributed.

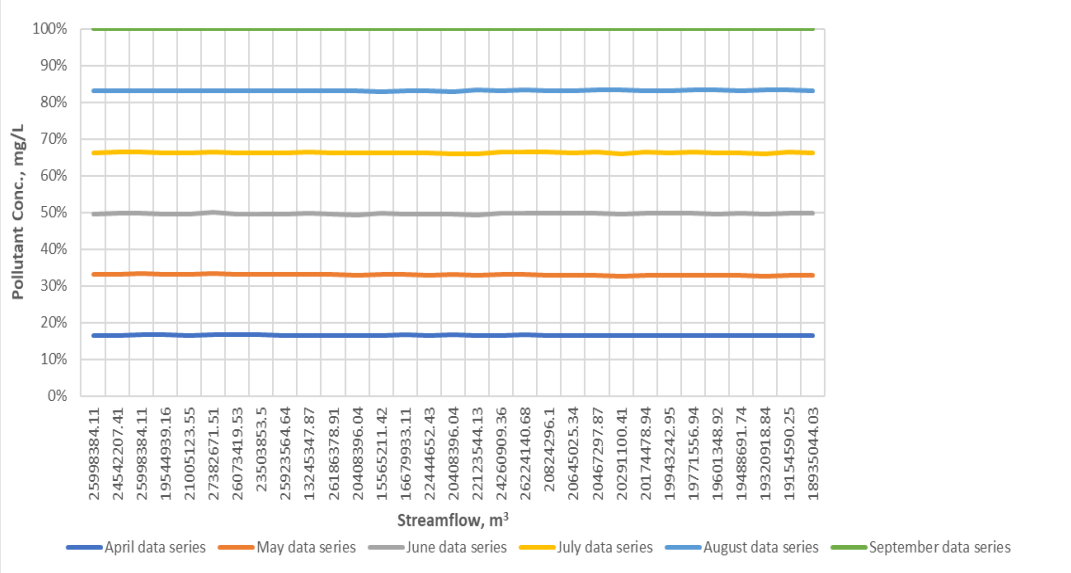


Figure 2: Percentage monthly effects of pollutant concentration

From Figure 2, it shows that the month of April pollutant concentration saturated level in the reservoir is below 20%. This further confirmed the dilution pattern

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system that occurred within the reservoir and also demonstrated the little or no runoff or rainfall contributions as obviously observed and known fact, but the only existing and available water in the storage controlled the system, while the month of May just raised above 30 % with rate of change value of -0.003 (slope) (Table 1) refers to as weak change on the downward trend. The month of June demonstrates a **transition period** as the saturation level reached 50 %. The condition suggests two hydrological events of the Kangimi reservoir catchment, the period of persistence rainfall, and the time at which reservoir received maximum runoff after overland moisture condition has been satisfied. At this period of the year the reservoir has completed its flushing, enrichment and dilution processes, though, the processes look weak with slope value 0.0085 (Table 1), but relevant when compared with others as presented in the same table. Furthermore, the months of July and August streamflow enriched the reservoir with pollutant concentrations at saturation level of 68% and 83%, respectively (Figure 1). The condition that suggests the relevant and significant enrichment, dilution, and flushing processes of pollutant concentration into the reservoir, at highest statistical mean value of 5.56mg/L, though without significant average change rate (0.0084 and 0.0092, respectively) (Table 1.0). This is to say, the months of July and August are very sensitive to runoff flows and pollutant concentration, although, not enough to say strong level.

The saturation level for the month of September was 99% with downward slope (-0.002) (Table 1) suggesting dilution pattern (Chen *et al.,* 2020) which could be noticed in Figure 1 as the curve gradually disappeared. At this period, it can be described that the enrichment, flushing and neutralization processes are returning from optimum value to dilution pattern of normal streamflow condition when no runoff or direct rain water contributes to the reservoir the condition which agreed with Weiler and McDonnell (2006) report.

Conclusion and Recommendation

The model simulation provides the dynamics and trends insights into storm event for the months of April to September pollutant concentrations into Kangimi reservoir storage. The reservoir system responded to the seasonal event as pollutants responded to streamflow discharge variability. The relationships that exist between the pollutant-streamflow for the months of April and May revealed a slight dilution at the beginning and subsequently flat to zero to the end. This revealed that the factor of streamflow discharge controlled the pollutant

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concentration as the pattern approaches flat and could also be explained that it is sensitive to available streamflow when little or no runoff inflows from the catchment sources.

In the months of June and August a substantial sensitivity to streamflow discharges as pollutant concentration become optimal suggests the regular surface inflows, direct rainfall and completion of mixing and flushing processes in the storage.

Individually, the month of June complete a transition period as the saturation level reached 50% and distinctive two hydrological events of the Kangimi reservoir catchment revealed, the period of regular rainfall, and the time at which overland moisture condition of the reservoir catchment satisfied. At this month (June) of the year the reservoir has completed its flushing, enrichment and dilution processes with weak upward change (0.0085), but may be significant when compared with others months of the year.

Another interesting result is in the month of September where pollutants saturation level reached 99% with downward change direction (-0.002) suggesting dilution pattern, end of the enrichment session, flushing, and neutralization processes. At this period, it can be described that the enrichment, flushing and neutralization processes have returned from optimum value to dilution pattern of normal streamflow condition when no runoff or direct rain water contributed to the reservoir storage.

In conclusion, the overall agreement of model with simulated data gave a baseline value of 1.0 shows that the system output is a dependent of the existing input (streamflow), and the output is connected in a linear manner. Therefore, it can reliably be said that pollutant concentration does little effects in a general condition of the Kangimi dam reservoir live time as range of concentration of the pollutants still remained between the range values of 5.42 – 5.56 mg/l despite at the peak of the raining season of the Kangimi watershed. The study therefore recommends the following:

i. The result of the sensitivity analysis may need further verification so that the model generality acceptance will be highly applauded.
ii. Using other pollutants parameters on the model in needed to further improve the model usefulness in Kangimi dam water management and early alertness for serious pollution.
iii. The study focused on raining season period of only one rainfall season, it is advisable to look at various rainfall events or patterns effective and efficient water management.

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iv. The drought period at the dam is also needed to be studied since the model only focused on raining season for the prediction.

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