SEASONAL VARIATION OF THE RELATIONSHIP BETWEEN SUSPENDED SEDIMENT AND RIVER DISCHARGE

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ABSTRACT:

Information on measured sediment load is important in the calibration of hydrologic models used in sediment yield prediction. The purpose of this study was to relate sediment load to discharge at a river section. An appropriate section was selected at the Lotanyanda river, Limpopo, South Africa. Depth integrated sediment samples were collected once a day on various dates at an appropriate interval and analyzed to determine the sediment concentration and turbidity. The water level and water temperature readings were also taken at the time of sediment sampling. Information obtained on sediment concentration and discharge was used to determine the sediment load on the dates when sampling was done commencing autumn through winter in the year 2016. Based on the values of measures of performance that included R², NSE, RMSE, PBIAS and RSR, performance of predicted sediment concentration based on sediment rating curves was very good and could be used for predicting sediment load. The measures of performance, however varied from season to season. The relationship between sediment load and discharge varied from one season to another and the quality of fit (R²) based on regression analysis differed from one season to another. Knowledge of sediment load discharge relationship can be used in sediment load prediction based on discharge information.

Keywords: Sediment sampling, regression analysis, seasonal variation, Sediment load.
1.0 INTRODUCTION

Sedimentation in rivers affects the raw water quality resulting partly from buildup of suspended solids while also posing serious threat to available dam storage capacity (Andualem and Yonus, 2008). Estimation of observed sediment load which may be determined through measurement sediment in rivers provides useful information for calibration of sediment prediction models (Shen and Julien, 1993). Besides, observed data is important is establishing the accuracy of models in simulating hydrologic system processes that they represent (Baffaut et al., 2015) which include river flow and sedimentation. There is growing interest in accurate determination of suspended sediment and sediment associated chemical constituents (Horowitz et al., 2015), reasons including issues associated with Contaminant transport, water quality trends, reservoir sedimentation and erosion and soil loss. The significant role of sediment regime in river basin management has been neglected due to lack of data occasioned by difficulty, costs, expense and time needed to measure the data (Fortesa, et al., 2021). Sediment load may be calculated from knowledge of sediment concentration and the corresponding discharge which is be calculated from river stage based on known relationship between stage and discharge. Sediment concentration at selected stream sections may be determined by manual collection of the sediment using appropriate sediment samplers or may be done automatically using weirs instrumented with automatic samplers to collect flow weighted sediment samples (Baffaut et al., 2013) which are then processed using evaporation method. Sediment rating curves are used to establish the relationship between sediment concentration and river discharge. The relationship between log transformations of sediment concentration and discharge based on regression may be linear or polynomial of order 2 or 3. The R2 value (coefficient of determination) computed from regression measures how close the data fits the regression line (Chhetri, et al. 2016) is used to establish the relationship among sediment concentration, sediment load and stream discharge. The relationship varies spatially and temporally. The temporal pattern of sediment concentration also does not necessarily follow that of discharge. The purpose of this study is to establish the relationship between sediment load and sediment concentration to river discharge to form a basis upon which sediment load may be predicted from observed discharge.

2.0 METHODOLOGY

2.1 SITE DESCRIPTION

The site chosen for sediment data collection was at the Latonyanda River upstream of the gauging station designated as A9HO27 which is the outlet of a sub catchment in the Latonyanda river catchment. The gauging station is instrumented to record river stage which can be converted to discharge using the stage discharge relationship. A weir is installed at the gauging station and therefore has a predetermined relationship between river stage and discharge being a pre-calibrated structure. The station has a data logger which records stage readings at 12-minute intervals. The DWAS technical staff visits the station once a month to download the water level readings and also take the water stage records from a gauge plate upstream of the weir. The gauging station is shown in Figure 1.
2.2. SEDIMENT SAMPLING METHOD

Sediment was sampled from a selected section upstream of the gauging station. The section was the best possible location determined after several visits to the site accompanied by trial sampling at different flow volumes and using various sampling methods which included the use of open mouth bottles to collect water by hand holding to use of a taylor made sampler manufactured by an artisan specially designed to use plastic honey jars as sample containers. It is fitted with a head piece which has an inlet and breather pipes. The head piece consists of milled plastic block with a jar lid permanently attached to the inside. The breather pipe allows air to exit the jar so that water can enter via the inlet tube. It allows one to sample from the bank or a structure and to obtain depth-integrate samples in shallow, accessible water courses (Bannatyne, 2016).

Equal width depth integrated samples were acquired from the selected river section upstream of the weir. The river section was divided 11 segments of equal width giving a total of ten (10) verticals. Depth integrated samples were collected from each vertical based on equal width sampling technique. The ten samples were collected in the 500ml bottles. The depth of each vertical was also determined using a steel tape measure immersed into the water. The water temperature was determined each time the sediment was sampled. The samples were then transported to the appropriate laboratories for analysis to determine turbidity and sediment concentration. The process of sediment sampling is illustrated below (Figure 2).
2.3 ANALYSIS OF SAMPLES FOR DETERMINATION OF SEDIMENT CONCENTRATION

Sediment samples collected from the stream were analysed for suspended sediment concentration (SSC) in the soil science laboratory, School of Agriculture. The filtration method (Baffaut et al. 2013) was used in the analysis of sediment and involves analyzing for sediment and involves using a 50ml pipette to collect a sub sample which is then filtered through a pre weighed dried filter paper of 11μm pore size into conical flask. The filter paper containing the filtered sediment was dried and reweighed to determine the sediment concentration. The sediment concentration was determined as the ratio of the dry weight of sediment and the volume of pipetted sub sample.

\[
SSC = \frac{w_d}{v_p} \quad \ldots (1)
\]

Where SSC in g/cm\(^3\), \(w_d\) the weight of dry residue and \(v_p\) the volume of pipette = 50ml

\[
SSC \text{ (kg/m}^3\text{)} = SSC \text{ (cm}^3\text{)} \times 1000.
\]

The average sediment concentration for the ten samples was the determined and considered the average suspended sediment concentration at the river section. Figure 3 illustrates the process of determining sediment concentration.
2.4 Estimation of Sediment Load.

The sediment load was determined as the product of suspended sediment concentration and discharge. Appropriate sediment rating curve was established through regression plot between suspended sediment concentration and discharge. On each day that sediment was sampled during the winter season, the average sediment concentration was determined. The corresponding discharge was also calculated from the stage reading using the appropriate rating table. Regression was performed for linear or nonlinear of 2nd or 3rd order. Regression analysis that yielded the best possible value of coefficient of determination ($R^2$) for the rating curve was chosen to relate sediment concentration and discharge. Hence the relationship between sediment discharge and concentration was established. This relationship was then used in determining sediment load. For the range of discharges determined during the winter season during when data was collected, the corresponding SSC was predicted from the rating curve. The sediment suspended sediment concentration (SSC) can be computed from the equation

(Chetri et al., 2016)

$$\text{Sediment load} = \text{SSC} \times Q,$$

Where SSC is the suspended sediment concentration (mg/l); Q is discharge derived from the rating curve (m$^3$/s) the discharge in m$^3$/s.

$$\text{SSC} = \frac{[(A-B)] \times 1000}{C} \quad \cdots (2)$$

Where A is the weight of filter paper + dry residue, B the weight of dried filter paper in mg and C volume of filtered water sub sample.
3.0 RESULTS AND DISCUSSION

3.1 RELATING OBSERVED SEDIMENT CONCENTRATION AND DISCHARGE

According to Hapsari et. al., (2019), the accuracy of the rating curves is dependent on seasons among other factors, and so recommends separation of sediment rating curves based on seasons owing to seasonal variability of prevailing conditions. The author further reports that a better understanding of sediment movement is obtained using sediment rating curves in which the sampling periods is divided into winter, spring, summer and autumn. Figure 4 illustrates the relationship between observed river flow and measured suspended sediment concentration (SSC) for the various seasons used in this study.

Evidently, there is a positive correlation between the two variables for all the seasons based on linear regression. The significance of the relationship between SSC and discharge is determined by complex combination of factors (Galloway et al., 2011) that include variability of SSC for the period of observation and the limited range of river flow observed during the seasons. The inputs of sediment to the stream vary spatially and over time thereby affecting the relationship between SSC and observed river flow.

![Figure 4: Relation between suspended-sediment concentration and river discharge in the Latonyanda river during various seasons.](image)
3.2 SEDIMENT RATING CURVES

Sediment rating curves relate discharge to sediment concentration. This may be achieved through regression which may be linear, nonlinear that could be polynomial of order 2, 3 or higher. The sediment rating curve was generated for the station under study based on the log – log regression relating suspended sediment concentration and discharge as proposed by Horowitz (2003).

Figures (a), (b), (c) and (d) shows the regression curves based on the graphical plot of log transformations of concentration (mg/l) and discharge (m$^3$/s) at the selected station river section upstream of the gauging station A9H027 at the Latonyanda river for various seasons as indicated.

\[ y = 274.27x^4 + 788.26x^3 + 818.98x^2 + 357.83x + 55.782 \]
\[ R^2 = 0.80 \]

Figure 5(a): Sediment rating curve based on the best polynomial regression for winter season
Figure 5(b): Sediment rating curve based on the best linear regression for the spring season

\[ y = 13.158x + 15.621 \]
\[ R^2 = 0.82 \]

Figure 5(c): Sediment rating curve based on the best polynomial regression for the summer season.

\[ y = -29.909x^3 - 103.87x^2 - 118.06x - 41.534 \]
\[ R^2 = 0.94 \]
The polynomial regression that yielded the highest possible value for $R^2$ varied from one season to another. During the winter season, polynomial regression of order 5 yielded the highest possible value of $R^2 = 0.80$ based on a plot of log C against log Q. The linear regression yielded the best possible value of $R^2 = 0.82$ for the spring season while polynomial regression of order 3 yielded the best possible value of $R^2 = 0.94$ in the summer season and polynomial regression of order 5 yielded the best value of $R^2 = 1.0$ for the autumn season. It is, however, observed by Goransson et al. (2013) that the relationship between sediment concentration and discharge is not straightforward being influenced by factors that include catchment sediment supply, intensity and spatial distribution of rainfall, human activities and urbanization among others.

3.3. COMPARISON OF OBSERVED AND PREDICTED SUSPENDED SEDIMENT CONCENTRATION.

Table 1 shows the observed sediment concentration based on analysis of collected sediment samples and the predicted suspended sediment concentration for the four seasons during when data was collected.
Table 1. Observed and predicted sediment concentration on sediment sampling dates.

| Date       | Observed SSC (mg/l) | Predicted SSC (mg/l) |
|------------|---------------------|----------------------|
| Winter     |                     |                      |
| 25/05/2016 | 240.0               | 266.37               |
| 27/05/2016 | 580.0               | 577.57               |
| 08/06/2016 | 180.0               | 177.63               |
| 22/06/2016 | 420.0               | 315.23               |
| 06/07/2016 | 240.0               | 315.23               |
| 20/07/2016 | 260.0               | 257.58               |
| 27/07/2016 | 300.0               | 266.42               |
| Spring     |                     |                      |
| 02/08/2016 | 20.0                | 34.58                |
| 16/08/2016 | 180.0               | 260.87               |
| 23/08/2016 | 400.0               | 260.87               |
| 30/08/2016 | 360.0               | 260.87               |
| 13/09/2016 | 60.0                | 34.58                |
| 20/09/2016 | 180.0               | 260.87               |
| Summer     |                     |                      |
| 11/10/2018 | 180.0               | 160.51               |
| 18/10/2016 | 140.0               | 160.51               |
| 01/11/2016 | 180.0               | 182.52               |
| 14/11/2016 | 320.0               | 322.85               |
| 18/11/2016 | 20.0                | 322.32               |
| Autumn     |                     |                      |
| 23/02/2017 | 570.0               | 581.8                |
| 02/03/2017 | 700.0               | 703.29               |
| 09/03/2017 | 230.0               | 230.17               |
| 16/03/2017 | 310.0               | 310.35               |
| 04/05/2017 | 430.0               | 429.96               |
| 11/05/2017 | 420.0               | 419.98               |
A linear regression between observed and predicted suspended sediment concentration is shown below (Figure 6) for the various seasons of the year.

\[
y = 0.8389x + 44.942 \\
R^2 = 0.84
\]

\[
y = 0.6116x + 63.121 \\
R^2 = 0.65
\]

\[
y = 0.9824x + 5.7419 \\
R^2 = 0.97
\]

\[
y = 1.0155x - 4.2645 \\
R^2 = 1.0
\]

Figure 6: Comparison of observed and predicted suspended sediment concentration (SSC) for various seasons.
The coefficient of determination $R^2 > 0.5$ for all the seasons implying acceptable quality of fit. The percentage difference between the averages of the observed and predicted sediment concentration was found be about 1.94% for winter season, 7.3% in spring season, 0.8% in summer and 0.6% in the autumn. The Nash Sutcliffe efficiency (NSE) for comparison of observed and predicted sediment concentration is tabulated for the various seasons of the year as well as values of other statistical performance measures (Table 2). These included Root Mean Square Error, RMSE – observation standard deviation ratio (RSR) and Percentage Bias (PBIAS) (Table 2). These tabulated values of performance measures show that the prediction of suspended sediment concentration is very good and can be used in sediment load or flux estimation. The sediment load was determined as the product of suspended sediment concentration and observed discharge estimated from the stage - discharge rating equation.

### Table 2: Values of statistical performance measures for comparison of observed and predicted sediment concentration.

| Season | $R^2$ | NSE  | PBIAS | RSR |
|--------|-------|------|-------|-----|
| Winter | 0.84  | 0.84 | 2.17  | 0.40|
| Spring | 0.65  | 0.64 | 7.4   | 0.60|
| Summer | 0.97  | 0.97 | -0.91 | 0.17|
| Autumn | 1.0   | 1.0  | -0.74 | 0.03|

#### 3.4 RELATING SEDIMENT LOAD AND DISCHARGE

Figure 7. Shows the linear regression analysis between the sediment load calculated from the suspended sediment concentration and observed discharge at the river section during the four seasons of the year. The quality of fit based can be considered as acceptable based on the value of coefficient of determination ($R^2 > 0.5$) for all the seasons. The relationships can therefore be used in predicting suspended sediment load from observed discharge data where sediment sampling has not been done.
3.5 TEMPORAL VARIATION OF SEDIMENT CONCENTRATION AND DISCHARGE

Figure 8 shows the time variation of streamflow and suspended sediment concentration at the Latonyanda river during all seasons of the year when sediment data was collected and analysed for concentration while taking river stage readings.

From the above indicated figure, the peak of SSC and that of discharge occurred at the same time particularly during relatively high flows which occurred after heavy rain on 27th May 2016. However, during other times there is no correspondence in pattern between the observed river discharge and SSC. The relationship between SSC and river discharge varies from one river to another and from
section to section within the same river. Even under identical streamflow, SSC may still differ (Galloway et al., 2011) since the runoff generating conditions could be different. Cheng et al. (2018) recognizes that sediment loads (which is dependent on sediment concentration) and river discharges are different process and much as discharge affect sediment load, the sediment amount is determined by other factors including soil texture, land use topography and human activities.

4.0. CONCLUSION

The relationship between sediment load and discharge yielded a very good quality of fit for all seasons based on linear regression. This relationship can be used in predicting sediment load from discharge for the range of discharges observed during the period of observation.

Good relationships were observed between observed and predicted sediment concentration based on developed sediment rating curves. Measures of quality of fit that included Nash Sutcliffe efficiency, coefficient of determination, percentage bias and percentage difference between observed and predicted values all of which yielded acceptable values.

The temporal pattern of sediment concentration for the period of observation does not necessarily follow that of the river discharge except during high flows when the timing of the peak discharge and that of sediment concentration coincide.

The order of polynomial regression that yielded the best value of coefficient of determination between sediment concentration and river discharge varied from one season to another.

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