The Relationship between Turbidity and Total Suspended Solids in the Blue Nile River at Khartoum

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Abstract
Estimation of sediment characteristics in the Blue Nile River is of great importance particularly for the water treatment plants in Khartoum State. It represents a great challenge to water supply authorities due to the high variation of the sediment load through the year. It varies from 8 NTU in the recession time to more than 30000 NTU during flood season, this when coupled with the limitation of sedimentation measuring equipments makes the operation of water treatment plant (WTP) quite difficult during flood season.

Turbidity measurement with nephelometric turbidimeters is considered a good method for estimating sediment concentrations in rivers.

The relation between turbidity (T) and Total Suspended Solids (TSS) is directly proportional due to the tendency of suspended solids to attenuate or scatter light.

The main objectives of this paper are to establish a relationship between (T) and (TSS) for the Blue Nile River at Khartoum and to assess the statistical significant of this relationship. Other specific objective is to identify the degree of confidence that the relationship is close to.

The paired turbidity and TSS data used in this assessment were obtained from the central lab of Khartoum State Water Corporation (KSWC). A Regression analysis tool is used to investigate the relationships between the turbidity and TSS in order to ascertain the causal effect of one variable upon another. The correlation coefficient (R) is applied to determine the strength of the relationship. Significance of the relationship and degree of confidence are carried out by applying the statistical analysis through Hypothesis and Random Error Analysis. It is concluded that while the relationship between turbidity (T) and TSS depends on several factors, it shows strong positive linear relationship with high degree of correlation for the total, rising and falling limbs of the flood hydrograph.

***Keywords*:** Sedimentation, Turbidity, Total Suspended Solids (TSS), Suspended sediments Concentration (SSC), Regression analysis

1. INTRODUCTION

1.1. Total Suspended Solids (TSS) and Suspended Solid Concentration (SSC)

In the literature there is an erroneous understanding between Total Suspended Solids (TSS) and Suspended Sediments Concentration (SSC). Total Suspended Solids (TSS) and Suspended Sediment Concentration (SSC) both are laboratories techniques used to indicate the amount of suspended matter exist in water. TSS method was originally developed for use with wastewater samples, but it has been widely used as a measure of suspended martial in stream samples.

TSS and SSC readings are based on filtered and dried water samples. Both of them are measured in milligrams per liter of water (mg/L). TSS encompasses any particles larger than 2 microns in diameter. Particle smaller than this is considered as a dissolved solid.

The main difference between TSS and SSC is in the amount of sample of water analyzed. After filtering a water sample through a 2-micron filter, the particles are dried and weighed to determine suspended solids. When an entire sample is filtered, dried and weighed, the American Society for Testing of Materials considers the measurement to be the SSC. If a water sample is further subsampled, the subsequent mass measurement will be the TSS measurement. This can be done by shaking/stirring and pouring from the sample bottle (EPA method) or by stirring and collecting a sample with a pipette (APHA method). The EPA method is considered more consistent than the pipette method, (FISP, 2006).

According to Kemker and Christine, 2014, for samples with fine suspended particles (less than 53 microns), the total suspended solids measurement and the suspended sediment concentration will be both precise and accurate relative to the true concentration. However, if larger (medium-coarse) particles are included in the sample, sub-sampling can often introduce error into the TSS measurement. The larger the particle, the more likely that it will not be included in the sub-sample due to the rapid settling of larger particles.

Other difference between TSS and SSC based on the water science literature is that while the TSS represents the suspended material concentration which includes silt, clay, plankton, organic and inorganic waste, the SSC refers to the sediment that is supported by the upward components of turbulence in a stream and that stays in suspension for an appreciable length of time.

In the Blue Nile, the majority of suspended material particularly during the flood season consists of clay and silt particles, the presents of plankton and organic waste is rare found and can be neglected. Khartoum State Water Corporation (KSWC) usually uses Spectrophotometer equipment for measuring TSS. The water sample is taken by shaking and pouring from the sample bottle according to (APHA method).

In line with the above justifications, the TSS and SSC can be used interchangeably when expressing the presence of suspension material in water samples representing the Blue Nile.

1.2. Relation between Turbidity (T) and Total Suspended Solids (TSS)

Turbidity is caused by particles and colored material in water. It can be measured relative to water clarity, directly with a turbidity instrument such as a turbidimeter or turbidity sensor. Turbidity meters use nephelometry (90 degree scattering) or other optical scatter-detection techniques for fast, accurate turbidity measurements on water samples.

Total suspended solids (TSS) are the main cause of turbidity. The most common, and accurate method of measuring suspended solids is by weight. To measure TSS, a water sample has to be filtered, dried, and weighed. However the process is difficult and time-consuming. The second method is by using an instrument measuring wavelengths of light spectra which is called spectrometer.

The magnitude of turbidity T in water is proportional to TSS. Hence, the turbidity-TSS relation can be quantified through linear regression analysis (Walling, 1977; Gilvear and Petts, 1985; Buchanan and Schoellhamer, 1995; Lewis, 1996; Uhrich and Bragg, 2003; Lietz and Debiak, 2005).

Continuously monitored turbidity data enable computation of a TSS time series that can be used with its paired stream flow time series to compute continuous Suspended Sediment Load (SSL) without the routine need for interpolation or estimation.

Although measuring turbidity is easier than measuring suspended solids, more information is needed on their relationship. While a relationship can be established between turbidity and suspended sediments, this relationship can and will change spatially and temporally due to variations in sediment composition and stream energy (Rasmussen 1995).

There is no universal relationship between turbidity and suspended sediment concentration, but there is often a good correlation for individual streams. (Gippel 1995), stated that the relation between turbidity and suspended sediments concentration is largely confounded by variations in particle size, particle composition and water color. Similarly, Foster et al. (1992) state that turbidity is a function of not only suspended sediment concentration but also particle size, shape and composition as well as the color of water. It is recognized that these variables do not necessarily vary in a predictable way with water or sediment discharge. Hence, particle size, shape and composition and water color may introduce bias into the relation between turbidity and suspended sediment concentration (Foster et al. 1992).

Gippel (1995) states that the relation between turbidity and suspended sediments can take two basic forms, the linear and non-linear models. Which form is dependent on instrument design and the way particle size and composition vary with particle concentration.

For the linear model it is assumed that particle size and composition do not vary with concentration in a systematic manner (Gippel 1995). Foster etal. (1992) found that there is only a linear relation between suspended sediment concentration (SSC) and turbidity (T) when the properties of the particles are constant. When particle size varies with sediment concentration the non-linear model is applicable

The main objectives of this paper are to establish a relationship between T and TSS in the Blue Nile and to test the significant of this relationship. Other specific objectives are to investigate whether turbidity and TSS are linearly or nonlinearly positively or negatively related.

2. THE DATA

The data used in this study is collected from the Central lab of Khartoum State Water Corporation (KSWC). The center has archived data for turbidity and TSS since 2007 sampled in a regular daily base. The HACH turbiditmeter with an upper limit of 4000NTU is used to measure the turbidity and dilutions are generally carried out at higher turbidity. TSS is measured in the Central Laboratory by using HACh Spectrophotometer.

3. METHODOLOGY

In this study a simple regression techniques is used to find the relationship between turbidity (T) and total suspended solid (TSS). The two variables were postulated as dependent variable T and independent variable TSS in accordance with Lewis & others, 20002.

To evaluate the effect of seasonal variations of the two variables on the relation three regression models were developed. The first model was developed for the whole flood season which usually starts from mid of June to end of October. Then the data were divided into two groups. In one group a model was developed for the rising limb of the flood season which spans the period from mid of June to end of August and in the other group a model for the falling limb of the flood seasons that spans the period from first September to end of October was developed.

The regression model is assumed as:

$$\hat{T}_i = a + bTSS_i + \varepsilon_i \quad \text{.........................(1)}$$

Where:-

$\hat{T}_i$ = is the model estimate of T in NTU for day i

a = Intercept of the regression line on vertical axis

b = Slope of the regression line

TSS_i = the independent variable which represents TSS mg/l for day i

ε_i = error term of the model

The parameters of the model in equation 1 (a and b) are estimated by using the least square estimation method by minimizing the sum of square errors of the model. The least square values of the parameters are given by the following equations:

$$b = \frac{\sum_{i=1}^{n}\left(TSS_i - \overline{TSS}\right)\left(T_i - \overline{T}\right)}{\sum_{i=1}^{n}\left(TSS_i - \overline{T}SS\right)^2}, \text{ and } b = \frac{n\sum_{i=1}^{n} T_i TSS_i - \sum_{i=1}^{n} T_i \sum_{i=1}^{n} TSS_i}{n\sum_{i=1}^{n} TSS_i^2 - \left(\sum_{i=1}^{n} TSS_i\right)^2} \quad \text{.........................(2)}$$

$$a = \overline{TSS} - b\overline{T} \quad \text{.........................(3)}$$

Where $\overline{TSS}$ and $\overline{T}$ are the mean values of TSS and T respectively and n is the number of data points used in the model.

The regression models goodness of fit tests were done using the following criteria:

a. Model Quality

The quality of the model is tested through testing two indicators. The first one is achieved by determining the coefficient of determination R^2 which expresses the goodness (fitness) of the model, given by equation (4)

$$R^2 = \frac{SSR}{SST} \qquad \ldots\ldots(4)$$

Where:-

SSR= Sum of Squares which is due to regression and is calculated from $\sum_{i=1}^{n}\left(\hat{T}_i - \bar{T}\right)^2$ which represents the variance accounted for by the model.

SST= Total sum of squares which is the sum of squared deviations of individual measurements from the mean and is expressed as $\sum_{i=1}^{n}\left(T_i - \bar{T}\right)^2$ which represents the initial variance.

The closer value of R^2 to +1 or -1 the good the regression model.

The second model quality indicator is the variance of the random error given by $\hat{\sigma}^2 = \frac{SSE}{n-2}$ where

SSE = SST - SSR

SSE is the Some of Squares Error and also called residual sum of squares which is the stochastic component of the variation of the dependent variable and is expressed as $\sum_{i=1}^{n}\left(T_i - \hat{T}_i\right)^2$

The larger value of the variance, the larger difference between the estimated values of the independent variables from the measured value and therefore the quality of the model is low.

b. Validity of the model

The validity of the model is the representation of the model to the relationship between the dependent and independent variables. It is tested statistically by applying F test.

This done by calculating the F statistics of the model given by:

$$F^* = \frac{SSR/1}{SSE/(n-2)} = \frac{MSR}{MSE} \qquad \ldots\ldots(5)$$

Under an assumed confidence level (α) (in this study 0.05 is used), the value of the critical F is obtained from the F distribution table denoted by $F_{1,n-2}^{1-\alpha}$. If $F^* > F_{1,n-2}^{1-\alpha}$ the represents the relation between the two variables.

c. Significance of the model parameters

The significant of the model parameters indicates the significance of the parameters in the model representation. This can be tested statistically using t test. This is done by estimating the variance, standard error of estimate and the t statistics for each parameter as follows:-

$$\sigma_a^2 = \sigma^2\left(\frac{1}{n} + \frac{\bar{T}SS^2}{\sum_{i=1}^{n}\left(TSS_i - \bar{T}SS\right)^2}\right) = MSE\left(\frac{1}{n} + \frac{\bar{T}SS^2}{\sum_{i=1}^{n}\left(TSS_i - \bar{T}SS\right)^2}\right) \qquad \ldots\ldots(6)$$

and

$$\sigma_b^2 = \frac{\sigma^2}{\sum_{i=1}^{n}\left(TSS_i - \bar{T}SS\right)^2} = \frac{MSE}{\sum_{i=1}^{n}\left(TSS_i - \bar{T}SS\right)^2} \qquad \ldots\ldots(7)$$

The t statistics of each parameter is given by equation (8)

$$t^* = \frac{Par}{SEE} \quad \text{...(8)}$$

Where Par is value of the parameter and SEE is standard error of estimate of the parameter given by the square root the variance of the parameter.

Under the same confidence level α = 0.05, the value of the critical *t* is obtained from the t distribution table denoted by $t_{1-\alpha/2,n-2}$

If $t^* > t_{1-\alpha/2,n-2}$ then the parameter is significant in the model representation and cannot be omitted

4. RESULTS AND DISCUSSIONS

As described earlier, the relation was established for three groups of data. For the whole period of the flood season; for the rising limb and for the falling limb of the flood. The results of the three scenarios are discussed bellow:-

4.1. The whole Flood Season Model

Applying the methodology discussed above the values of the parameters of whole flood season are a = 64.815 and b = 1.328. Therefore, the model of the whole is given by:

$$\hat{T} = 1.328 * TSS + 64.815 \quad \text{...(9)}$$

Figure (1) shows the scatter diagram along with the regression model. It can be seen that there is a positive linear relationship between Turbidity (T) and Total Suspended Solids (TSS), since the points seem to fit a straight line.

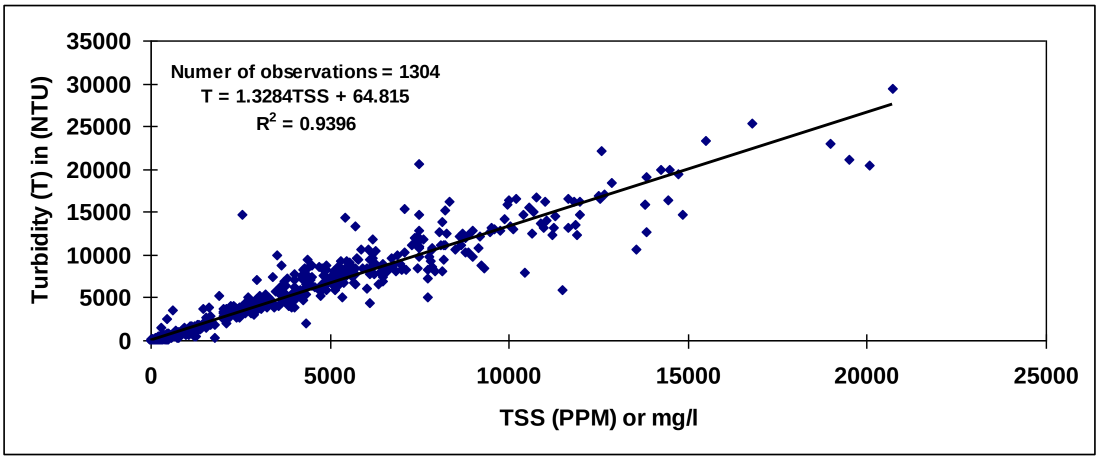

Figure 1: Relationship between (T) and TSS during Flood Season

Model quality

The values of SSR and SST were found to be 11762761027.43 and 12518964457.41 respectively. By substituting in Equation (4), the value of R^2 is ≈ 0.94

The variance of the random error $\hat{\sigma}^2$ was found to be equal to 580801.4

Validity of the Model Results

The calculated $F*$ is obtained from Equation (5) and it is found to be 20252.6,

From the F distribution table for α = 0.05, $F^{0.95}_{1,1302}$ = 3.84

Therefore $F^* > F^{1-0.5}_{1,1304-2}$ hence the regression model is suitable to represent the relationship between the two variables.

Significance of the model parameters

The variances of the parameters *a* and *b* are equal to 32.81 and 0.009327 respectively

From the *t* distribution table and with a degree of freedom df = n-2 = 1302 and confidence level (α) = 0.05, the value of $t_{1-0.05/2,n-2}$ = 1.96.

t_b^* is calculated from equation (8) and is equal to 141.52

Since $\left| t_b^* \right| > t_{1-0.05,1302}$, therefore the parameter *b* is significant.

t_a^* value is found to be 1.98. It can be seen that the critical *t* and calculated t_a* values are close (1.96 & 1.98 respectively), which indicates that the value of the line intercept is not very significant and can be dropped without significant loss of accuracy.

Table (1) and Table (2) present the summary of the statistical results of whole flood season model.

Table 1: Analysis Of Variance (ANOVA) Results for the whole Flood Season

	df	*SS*	*MS*	*F*
Regression	1.00	11762761027.43	11762761027.43	20252.64
Residual	1302.00	756203429.98	580801.41	
Total	1303.00	12518964457.41		

Table 2: Regression output for the whole Flood Season

Regression output				*confidence interval*	
variables	*coefficients*	*std. error*	*t (df=1302)*	*95% lower*	*95% upper*
Intercept	64.8147	32.8018	1.976	0.4645	129.1649
(X) TSS (PPM)	1.3284	0.0093	142.312	1.3101	1.3467

Setting the intercept to zero and recalculating, the value of the slope is found to be 1.337 with a little loss of R^2 which is not significant as shown in Figure (2).

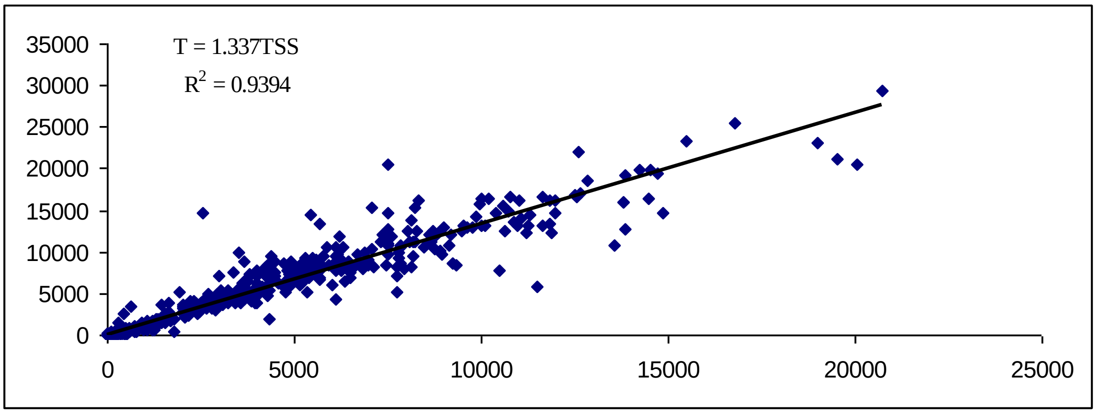

Figure 2: Relation between T and TSS when Setting the Interception of the Line to Zero for the whole Flood Season model

4.2. Results and Discussions for the Separated Rising and Falling of the Flood

Figure (3) shows that the relationship representing the rising time of the flood season is a positive linear relationship and the values of the parameters of the rising limb of the flood hydrographs are a = 17.492 and b = 1.33. Therefore, the model of the rising of the flood is described in equation (10) :

$$\hat{T} = 1.33*TSS + 17.492 \qquad (10)$$

The quality of the model was tested and R^2 was found to be 0.943.

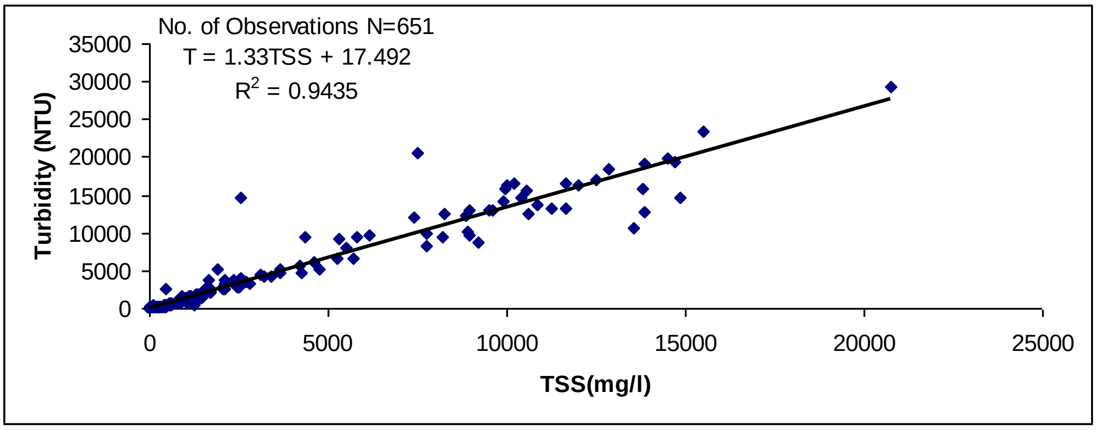

Figure 3: Relationship between (T) and TSS during the Rising Limb of the Flood Season

F^* value was calculated and it is = 10834.50.

From the F distribution table for α = 0.05, $F^{0.95}_{1,1302} = 3.84$. It can be seen that F^* calculated is greater than the critical F which indicate the validity of the model.

The significance of the parameters is tested by applying *t* test. The variance of *a* and *b* are found to be 36.3 and 0.000163 respectively, then the value of t^*_a and t^*_b were calculated and found to be 0.481 and 8140.24 correspondingly. The critical *t* is obtained from the t distribution table and it is = 1.962.

It can be seen that $\left| t^*_b \right| > t_{1-0.05,649}$, therefore the parameter *b* is significant. In the other hand $\left| t_a^* \right| \leq t_{1-0.05,649}$ which indicates that *a* coefficient is not significant and can be dropped with no significant change in R^2 as shown in figure (4)

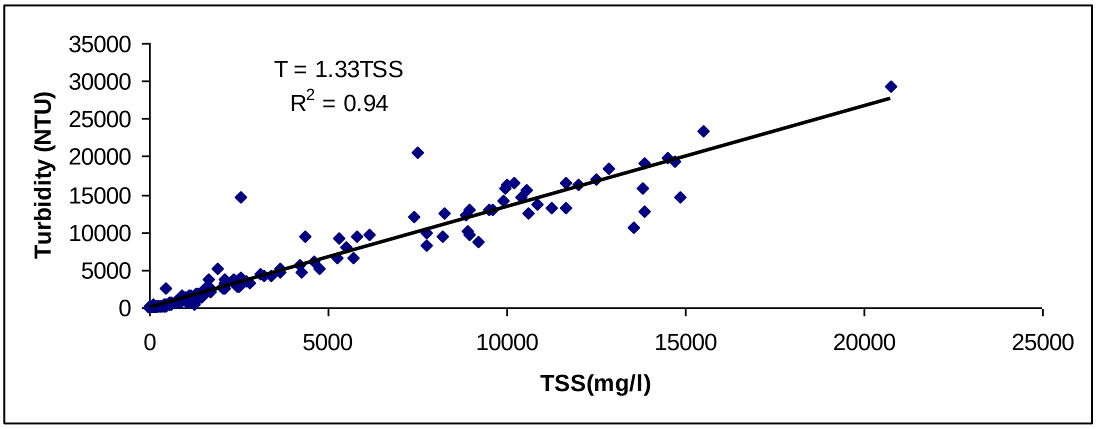

Figure 4: Relation between T and TSS when Setting the Interception of the Line to Zero for Data Representing the Rising Limb of the Flood Season

Table (3) and Table (4) present the summary of the statistical results of the rising limb of the flood hydrograph.

Table 3: Analysis Of Variance (ANOVA) Results for the Rising Limb of the Flood Season

Source	*SS*	*df*	*MS*	*F*
Regression	8,330,611,115.0955	1	8,330,611,115.0955	10834.50
Residual	499,013,720.1547	649	768,896.3331	
Total	8,829,624,835.2502	650		

Table 4: Regression output for the Rising Limb of the Flood Season

Regression output				confidence interval	
variables	*coefficients*	*std. error*	*t (df=649)*	*95% lower*	*95% upper*
Intercept	17.4916	36.3015	0.482	-53.7910	88.7742
TSS (PPM)	1.3305	0.0128	104.089	1.3054	1.3556

The relationship between T and TSS during the falling limb of the flood is illustrated in figure (5) and it is found to be positive linear relationship with a =128.24 and b =1.33 as described by equation (11)

$$\hat{T} = 1.32*TSS + 128.24 \qquad (11)$$

R^2 was found to be 93% which is slightly less than the coefficient of determinations for both equations representing the relation for the whole flood period and for the flood rising limb.
Same procedure described earlier was followed to test the validity and significance of the coefficients a and b.
Calculated F^* was found to be 8777.06 which is greater than the critical F obtained from the F distribution table which indicates the validity of the model.

The variance of a and b are found to be 57.47 and 0.000198 respectively. The values of $t^*_a = 2.23$ and $t^*_b = 6691.16$. Since both t^*_a and t^*_b are greater that the critical t= 1.962, this indicates that both a and b coefficients are significant.

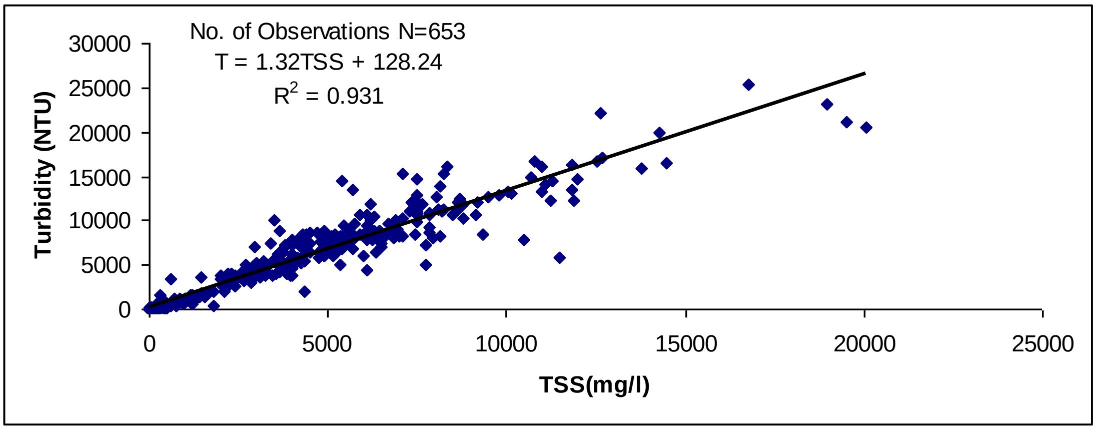

Figure 5: Relationship between (T) and TSS during the Falling Limb of the Flood Season

When setting the intercept to zero during the falling limb, it is found that the slope is slightly increased to become 1.33 with a little loss of R^2 =0.9304, Figure (6)

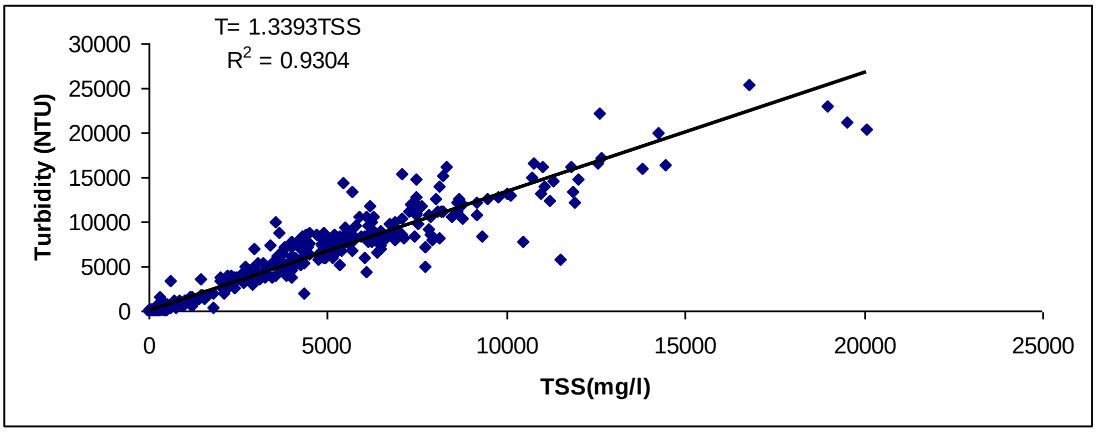

Figure 6: Relation between T and TSS when Setting the Interception of the Line to Zero for Data Representing the Falling Limb of the Flood Season

Table (5) and Table (6) present the summary of the statistical results of the falling limb of the flood hydrograph.

Table 5: Analysis Of Variance (ANOVA) Results for the Falling Limb

ANOVA table				
Source	*SS*	*df*	*MS*	*F*
Regression	12,378,286,123.6169	1	12,378,286,123.6169	8777.06
Residual	918,105,575.4883	651	1,410,300.4232	
Total	13,296,391,699.1052	652		

Table 6: Regression output for the Falling Limb of the Flood Season

Regression output				*confidence interval*	
variables	*coefficients*	*std. error*	*t (df=651)*	*95% lower*	*95% upper*
Intercept	128.2391	57.4739	2.231	15.3825	241.0956
TSS (PPM)	1.3208	0.0141	93.686	1.2932	1.3485

5. CONCLUSIONS

It can be concluded that the turbidity is potentially a viable surrogate measurement for determining total suspended solids (TSS) concentrations in the Blue Nile. Data collected from Khartoum State Water Corporation from year 2007 to year 2010 show a strong positive linear relationship for the whole period of flood season ($R^2 \approx 94$) between turbidity and TSS. When splitting the flood season into two parts that representing falling limb and rising limb, the relation is still strong positive linear with ($R^2 \approx 94$) and ($R^2 \approx 93$) respectively. It is also concluded that the values of intercept of the line with y_i axis can be set to zero without significant changes in the slope and R^2 except in the case of the falling limb in which the intercept is slightly significant. The general conclusion that can be drawn from this study is that the relations reached above are suitable to express the correlation between turbidity (T) and Total Suspended Solid (TSS) for the Blue Nile River at Khartoum State.

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7. SYMBOLS

APHA	American Public Health Association
ANOVA	Analysis Of Variance
df	Degree of Freedom
EPA	Environmental Protection Agency
KSWC	Khartoum State Water Corporation
NTU	Nephelometric Turbidity Unit
R	The Correlation Coefficient
SSC	Suspended Sediments Concentration
SSE	Some of Squares Error
SSL	Suspended Sediment Load
SSR	Sum of Squares due to Regression
SST	Total sum of Squares
T	Turbidity
TSS	Total Suspended Solids
WTP	water treatment plant
$\hat{\sigma}^2$	variance of the Random Error