Numerical Modeling of Sediment Transport Upstream of Al-Ghammas Barrage

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Abstract- Numerical modeling of sediment transport is the best tool to simulate sediment transport in a water body. The present paper uses numerical computational fluid dynamics "CFD" computer program Sediment Simulation In Intakes with Multiblock option "SSIIM" which considers flow and sediment equations in a three dimensional manner to predict the flow field and sediment transported upstream of Al-Ghammas Barrage, middle of Iraq on Euphrates river. It solves the Reynolds-averaged Navier-Stokes equations in three dimensions to compute water flow using the finite volume approach as discretization method, and also the convection-diffusion equation for sediment transport. The model was based on a three dimensional, non-orthogonal, structured grid with a non-staggered variable placement. The comparison between filed measurements and numerical results were considered to make the correct decision in this model. The verification showed good agreement between model results and observed data for suspended sediment concentration, depending on the value of coefficient of determination (0.94).

Keywords: Suspended sediment , three dimensional modeling , CFD, SSIIM, ADCP, Al-Ghammas Barrage.

1 Introduction

Waters flowing in natural streams and rivers have the ability to scour channel beds , to carry particles (heavier than water) and to deposit materials, hence changing the bed topography. This phenomenon (i.e. sediment transport) is of great economical importance : e.g. to predict the risks of scouring of bridges, weirs and channel banks; to estimate the siltation of a reservoir upstream of a dam wall; to predict the possible bed form changes of rivers and estuaries[1].

The sediment transport process is quite complex and occurs in various modes, like, bed load, suspended load, wash load etc. The type of the transport depends on the size of bed particles and flow conditions . In general, Coarser particles move along the bed by rolling and/or saltation (i.e., bouncing) in a thin layer as bed load, whereas finer particles are suspended into the water column and move as suspended load. The mode of transport for a given particle is largely affected by the sediment properties and flow regime of the region.

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The presence and movement of sediment causes many problems. The deposition and erosion of solid material of the beds and banks of channel increases bed deformation, which in turn will reduce the depth of water in some places and reduce the ability of the water way for navigation or hydraulic purposes. However, the raising of the river bed by the deposited materials increases the flood range to a great extent. As a result, large sums of money have to be spent to maintain the course of the river necessary for the hydraulic requirements[2].

Modeling river systems by using computers is a powerful tool for river engineering. In recent years, several numerical models have been constructed for simulating the 3D flow field , sediment transport and water quality, etc . In this study, the 3-D numerical sediment transport model SSIIM has been used to predict the flow field , distribution of sediment concentration and its quantities in a river reach (up/stream) of Ghammas barrage.

2 Description of the Study Region

The region of study locates in the Euphrates basin between the towns of Kifil (Hilla governorate) and Shinafiya (Al-Najaf governorate), extending between latitudes 31° 45′ 27.10″ **to 31° 46′ 22.98″ N and longitudes 44° 37′ 26.36″** to 44° 37′ **2.67″ E. The length of a study re** ach was about 2 Km upstream of barrage with an average width (55) m. In this region Ghammas Barrage is located on the Euphrates river at Al-Diwaniyah governorate in Iraq.

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The maximum design discharge is 1100 m^3/sec with the highest level ol. The barrage consist of five rectangular openings, each with a dimension (12x7) m supplied with a steel redial gate for water drainage. It is run electrically and manually. Ghammas Barrage was constructed during 1986 to control the flow in the middle Euphrates region. Figure (1) shows reach study location.

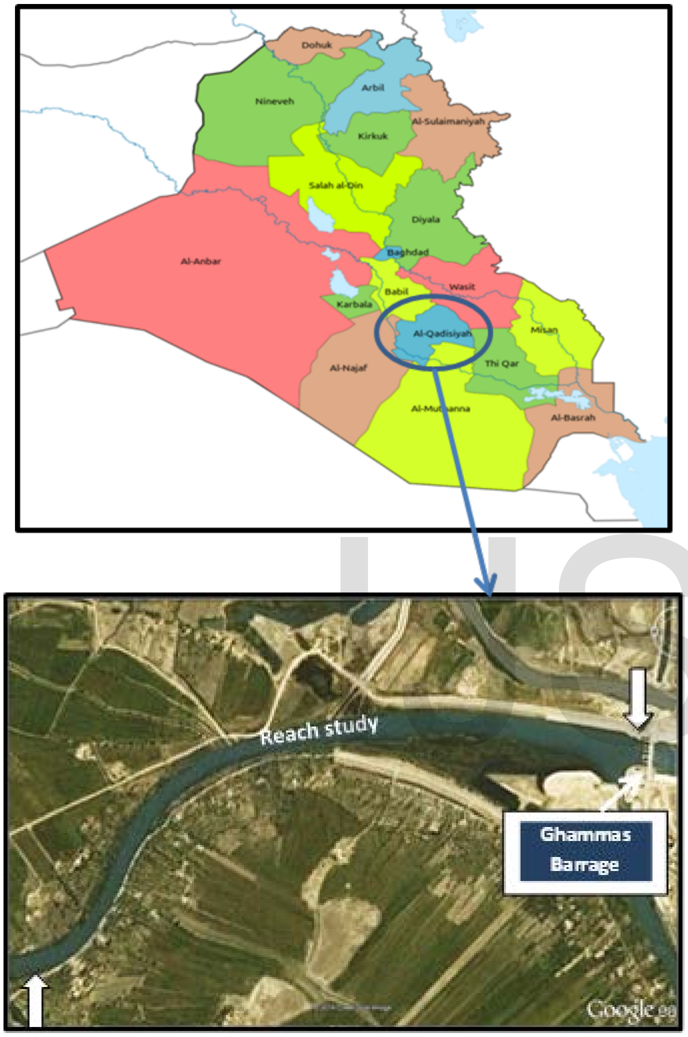

Fig.1 : Reach study location Comparison

3 The Numerical Model

The 3D CFD numerical model (SSIIM) is an abbreviation for Sediment Simulation In Intakes with Multiblock option. Dr. Nils Reidar B. Olsen, Professor Civil Engineering, Department of Hydraulic and Environmental Engineering at The Norwegian Institute of Technology, is developer of this program. It solves the Reynolds-averaged Navier- Stokes equations with the two equation k-e turbulence closure in three dimensions to compute the water flow using the finite volume approach as discretization method. SSIIM is based on the solution of the Navier-Stokes equations, with the k-e model.

This gives the water velocity and turbulence field which is used for solving the convection-diffusion equation for the sediment concentration. The three dimensional model is solved by the equations reported below[3].

3.1 Water Flow Calculation

In a three dimensional geometry, Navier-Stokes equations for turbulent flow are solved to obtain the water velocity. The k-ε model is used to calculate the turbulent shear stress. A simpler turbulence model can be used. This is specified on the function data in the code of Model (F 24) in the control file of SSIIM program.

The Navier-Stokes equations for non-compressible and constant density flow can be modeled as follow:

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = \frac{1}{\rho}\frac{\partial}{\partial x_j}\left(-P\delta_{ij} - \rho\overline{u_i u_j}\right) \qquad (1)$$

Where U is time-averaged velocity, u is velocity fluctuation, P is pressure; x_j are Cartesian space coordinates, δ_{ij} is Kronecker delta, ρ is fluid density. Knowing that in mathematics Kronecker delta equals:

$$\delta_{ij} = \begin{cases} 0 \; if \; i \neq j \\ 1 \; if \; i = j \end{cases} \qquad (2)$$

The left most term on the left side is transient term and the second term is convective term. The first term on the right hand side is the pressure term and second term is the Reynolds stress term. To evaluate this term, a turbulence model is required.

The default algorithm in SSIIM neglects the transient term. By means of different data sets this term, time step, number of inner iterations can be controlled.

The k-ε turbulence model

The k- ε model calculates the eddy-viscosity as:

$$\nu_T = c_\mu \frac{k}{\varepsilon^2} \qquad (3)$$

K is turbulent kinetic energy, defined as:

$$k = \frac{1}{2}\overline{u_i u_j} \qquad (4)$$

k is modeled as:

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\nu_T}{\sigma_k}\frac{\partial k}{\partial x_j}\right) + P_k - \varepsilon \qquad (5)$$

Where P_k is given by

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$$P_k = \nu_T \frac{\partial U_j}{\partial x_i}\left(\frac{\partial U_j}{\partial x_i} + \frac{\partial U_i}{\partial x_j}\right) \quad (6)$$

The dissipation of k is denoted ε, and modeled as:

$$\frac{\partial \varepsilon}{\partial t} + U_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\nu_T}{\sigma_k}\frac{\partial \varepsilon}{\partial x_j}\right) + C_{\varepsilon 1}\frac{\varepsilon}{k}P_k + C_{\varepsilon 2}\frac{\varepsilon^2}{k} \quad (7)$$

In all above equations 'c' are different constants. The k-ε model is the default turbulence model in SSIIM.

Wall laws

The wall law for rough boundaries is used, as given by Schlichting (1979):

$$\frac{U}{u_x} = \frac{1}{k}\ln\left(\frac{30y}{k_s}\right) \quad (8)$$

The shear velocity is denoted u_x and k is a constant equal to 0.4. The distance to the wall is y and the roughness, k_s, is equivalent to a diameter of particles on the bed.

3.2 Sediment Flow Calculation

SSIIM calculates sediment transport by size fractions. In the control file, each fraction is specified on an S data set, where the diameter and fall velocity is given. This data set has to be given when calculating sediment transport. The number of sediment sizes is given on the G 1 data set.

There are two methods to specify sediment inflow in the control file. One method is to give the inflow on the I data sets in kg/s. An I data set must then be given for each fraction. A vertical sediment concentration distribution according to the Hunter-Rouse Equation will then be used. This sediment concentration will be given over the entire upstream cross-section (i=1).

The other method to specify sediment inflow is to use the G 5 data set. Then the concentration is given for a specified surface at the boundary of the grid. The concentration is given in volume fraction, which is used in all calculations by SSIIM. It is possible to use both I and G 5 options simultaneously to specify multiple sources of sediments.

Specification of initial sediment fractions on the bed is done by using N and B data sets in the control file. The N data sets specify a number of sediment mixes. The distribution of the mixes in the various parts of the bed is given on the B data sets[3].

Conventionally sediment transport is divided in bed load and suspended load. The suspended load can be calculated with help of convection-diffusion equation for the sediment concentration, c, volume fraction in SSIIM.

$$\frac{\partial c}{\partial t} + U_j \frac{\partial c}{\partial x_j} + w\frac{\partial c}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\Gamma_T \frac{\partial c}{\partial x_j}\right) \quad (9)$$

Where 'w' represents the fall velocity of the sediment, U is the water velocity, x is a space dimension and Γ diffusion coefficient, which is taken from the k-ε model.

$$\Gamma_T = \frac{\nu_T}{S_c} \quad (10)$$

Where Sc is the Schmidt number, set to 1.0 as default in model. A different value can be given on the F 12 data set in the control file.

For calculating the suspended load, SSIIM program uses the formula that was developed by Van Rijn (1987) for computing the equilibrium sediment concentration close to the bed. The concentration equation has the following expression:

$$c_{bed} = 0.015\frac{d^{0.3}}{a}\frac{\left[\frac{\tau - \tau_c}{\tau_c}\right]^{1.5}}{\left[\frac{(\rho_s - \rho_w)g}{\rho_w \nu^2}\right]^{0.1}} \quad (11)$$

Where, C_{bed} is the sediment concentration , d is the sediment particle diameter, a is a reference level set equal to the roughness height , τ is the bed shear stress, τ_c is the critical bed shear stress for movement of sediment particles according to Shield's curve , ρ_w and ρ_S are the density of water and sediment respectively, ν is the viscosity of the water and g is the acceleration due to gravity.

4 Field and Laboratory Work

In this study, ten cross-sections were selected along the reach of Euphrates river to measure all the hydraulic variables and characteristics of sediments transported. The search area extends about 2 km upstream of Ghammas Barrage as shown in Figure (2). At each section, bed elevation, top width, area of cross sections, water level, water velocity and discharge were measured using the ADCP technology. SonTek river surveyor ; Figure (3) and Figure (4). These data were tabulated in Table 1. In addition to samples were taken from the mixture (water-sediment) and bed river to find suspended sediment concentration, particle size distribution and other properties of the transported sediment.

Bed material samples are taken for sampling verticals 1/4, 1/2, 3/4 width of the river cross-section. The obtained samples are mixed together and part of the mixture is taken to the laboratory for analysis[4].

The device (Van Veen Grab) which was manufactured

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corresponding to the specifications of global engineering used to get the bed material from the bottom of river ,see Figure (5).

Grain Size Analysis and specific weight were done for each bed sample, the results of these tests used as an input data in the model; Figure (6). The procedure followed to obtain the specific gravity of bed sediment materials was according to (ASTM D 854-00- Standard Test for Specific Gravity of Soil Solids by Water Pycnometer) [5]. The average value of specific gravity for all sections was (2.69).

Suspended sediments in the river were sampled to determine the sediment concentration. There are many methods of sampling available for different purposes .If the goal of sampling is to obtain information on the discharge of suspended sediment, the Depth of Integrated samples are taken. Also Depth-Integration sampling technique is used to obtain a sample that accounts for different sediment concentrations throughout the vertical profile of a water body [6]. In this study the sampling verticals were chosen at ¼, ½ and ¾ of the width of stream at each cross section. This procedure was very convenient and more practical for study reach [7].

Once suspended sediment samples were collected, the samples were filtered using filter papers. The filtration involves the removal of the solid matter from a sample by passing a known volume of liquid-solid mixture through a suitable filter. Each filter paper was pre-dried for 15 minutes in an oven at 105 C^0 and weighted , and then it was clipped to the filter funnel and moistened with distilled water. A known volume of the sample poured through the filter, and all interior surface of the cylinder were washed out into the filter funnel with distilled water. The filtration was accelerated with a vacuum pump connected to the flask of the filtration set. After the completion of filtration, the filter paper was dried for 60 minutes and reweighed. The difference between the two weights divided by the volume of the sample gives the concentration of the suspended sediments [8].

$$C = \frac{W2 - W1}{V} \qquad (12)$$

Where:

C=Concentration of suspended sediment in ppm or mg/l

W_1=Weight of dry filter paper in mg.

W_2=Weight of dry filter paper +suspended sediment in mg.

V=Volume of sample in liter.

Average concentration of suspended sediments (observed) at each section listed in Table 1.

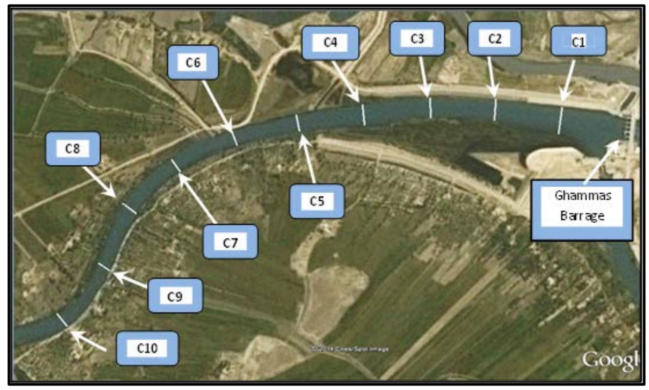

Fig. 2: The position of cross sections in the reach study, by Google Earth

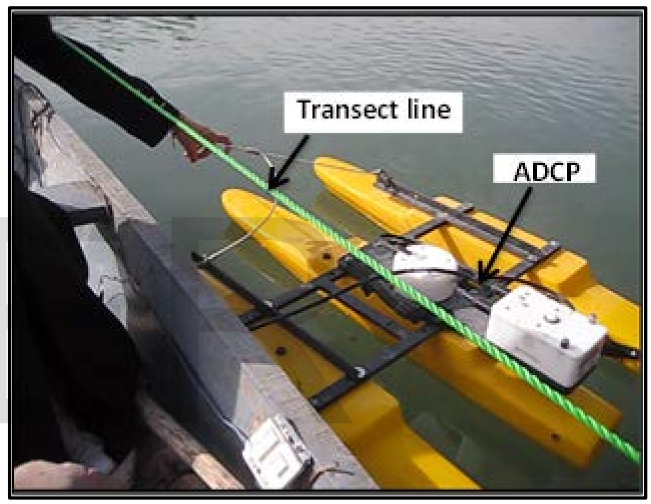

Fig.3: Fig. 3: SonTek River Surveyor ADCP

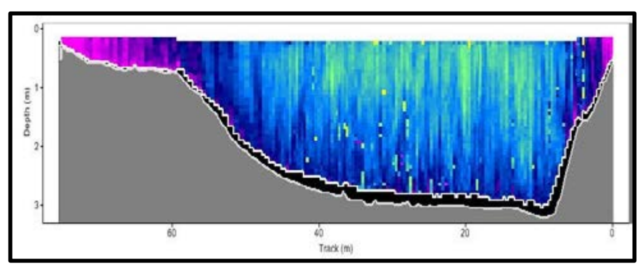

Fig.4: Profile of the River Bed for Cross section no.1 by ADCP

Fig. 5: Van Veen Grab Sampler

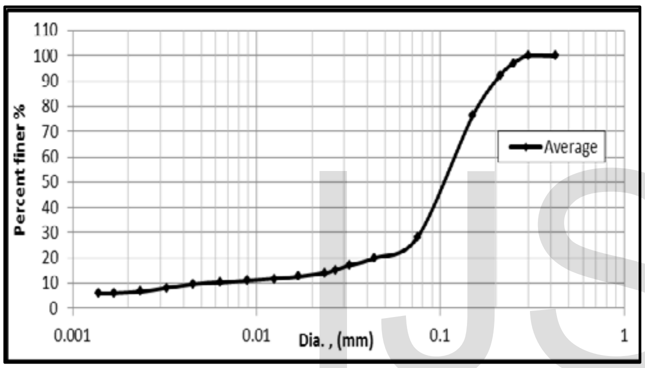

Fig.6:Average grain size analysis of bed samples in the whole reach

5 Sediment Discharge in Study Reach

The measurement of sediment discharge is essential to determine the quantity of sediment load. Then suspended sediment discharge can be calculated by multiplying the concentration with the flow discharge **(Van Rijn, 1993)**[1&9].

$$Q_S = C \times Q \times 0.001 \quad (13)$$

In which, Q_S = Suspended sediment discharge (kg/sec), C = Average concentration of suspended sediments in each section (mg/liter) and Q= water discharge (m^3/sec).

TABLE 1

Hydraulic properties, observed and computed values of average suspended sediment concentration for all sections .

Sec. No.	Area (m^2)	Top Width (m)	Velocity (m/s)	Q (m^3/s)	A.S.C. (PPM) Observed	A.S.C. (PPM) Computed
1	150.2	75.46	0.286	42.90	76.00	77.0
2	142.0	62.00	0.301	42.70	83.53	84.8
3	139.7	63.56	0.301	42.58	83.00	81.9
4	138.6	63.66	0.304	42.49	90.00	90.7
5	149.7	53.10	0.292	43.68	81.00	80.5
6	138.4	52.54	0.307	42.52	84.00	86.0
7	131.2	41.53	0.325	42.62	87.53	88.3
8	150.9	51.34	0.306	46.19	79.13	77.4
9	137.4	35.57	0.321	44.11	84.13	82.7
10	140.1	49.04	0.315	44.10	77.14	75.4

6 The Results From SSIIM

A. Secondary Flows in general study region

Secondary flows are defined as currents that occur in the plane normal to the primary flow direction. Their velocities are typically one order of magnitude smaller than the bulk primary velocity [10].

In the present study the secondary flow provoked by differences in centrifugal forces was observed as a result of the current deviation from its primary direction due to bends in the reach of study. Figure (7) and Figure (8) show the velocity vectors with scale in selected cross-sections. The vector arrows represent the velocity components v and w in transversal and vertical direction. The main secondary motion at the water surface is towards the outer bank ,which is farthest from the center of the turn. When, the flow elements reaching the wall will move in a down- or upward direction toward the inner bank which is nearest to the center of the turn , producing a circulation. The combination of this cross-circulation and the major flow direction results into flow spiral motion. The secondary flow near the bed leads to erosion at the outer bank and to deposition at the inner bank, resulting in a scour and a point bar.

B. Velocity Distribution in the Horizontal Plane (X-Y plane)

One of the products of model after running is the velocities distributions along the plane x-y plane, i.e., horizontal plane at different levels. By means of velocity vector with scale and contour lines, respectively. The results show the upper layers have higher velocities compare to lower one, although uniformity is maintained layer wise. The Figures (9,10,11 and 12) below showed these distributions as velocity vectors and as contour lines for selected levels.

7 The Sediment Distribution

A. Sediment Distribution in the Horizontal Plane (X-Y plane)

The results for region of study concentration showed high values at the bottom and where velocity is low. Further the sediment concentration is higher near end of bend than that the center of the cross-section in the mid channel. This is due to the drop in velocities in the end of bend after coming from high value because the centrifugal forces. Figure (13) shows the distribution of sediment in layer (level) No.3.

B. Sediment Distribution in the Cross- section (Y-Z plane)

The numerical model SSIIM showed the distribution of sediment concentration in each joint (i) and (j). The Figure (14) and Figure (15) showed the distributions of sediment in selected cross-section. In all sections, the concentration distributions taken high values near the bed. These values sometimes inclined between left bank to right bank depended on the curvature of river in region study.

The average concentration of suspended sediments (computed) at each section were listed also in Table 1.

8 Verification Data of Model

Verification can be defined as a process for assessing the numerical simulation uncertainty and when conditions permit, estimating the sign and magnitude of the numerical simulation error and the uncertainty in that estimated error.

However to verify numerical model with prototype the results were taken from field. In this study, the verify numerical model deals with sediment calculation. According to the results, the verification showed good agreement between model results and observed data for suspended sediment concentration and discharge. With determination coefficient 0.94 and 0.9078 as shown in Figures (16 and 17).

One reason for the deviation between measured and calculated data can be due to some lack of accuracy in the measurements of velocities and to the geometry of the reach. The software, estimate the bed forms between the consequent sections according to the data at these sections. This will lead to the geometry to be inexactly modeled. The other reason for the deviation between measured and computed velocities and sediment concentration was thought to be the size of cell in the model. Reducing the size of the grid cells in areas of small horizontal distance, will probably increase the accuracy in these areas.

The decision of number of grid in each direction must be taken with experience in numerical modeling. The large numbers of node make the model more time consumption to solve the equations at each node in three dimensions. At the same time the large number of grids make the model more accuracy.

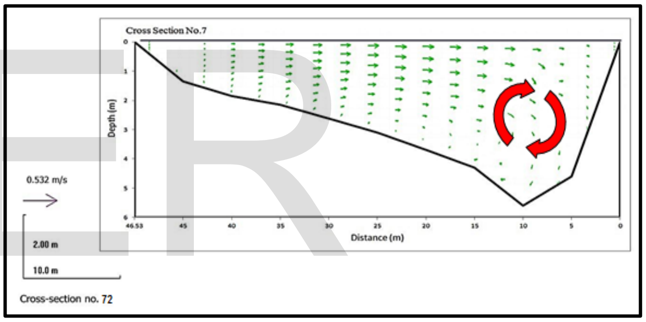

Fig. 7: The secondary flow as velocity vectors for cross-section no.7 by SSIIM Model

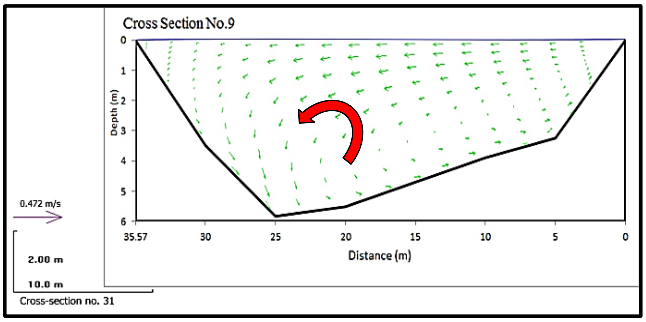

Fig. 8: The secondary flow as velocity vectors for cross-section no.9 by SSIIM Model.

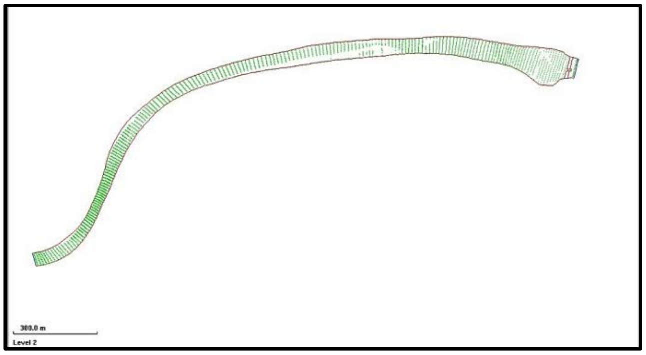

Fig. 9: Velocity Vector in x-y Plane at Level 2" Above the Bed"

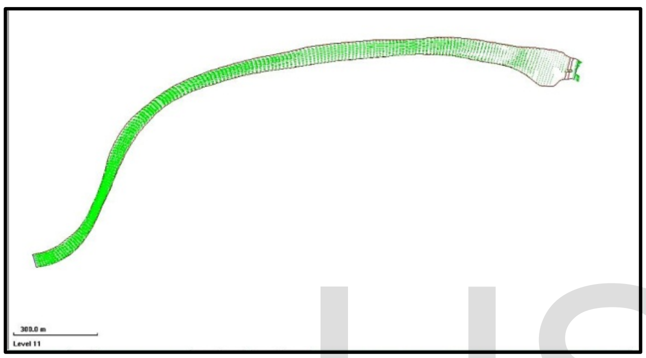

Fig. 10: Velocity Vector in x-y Plane at Level 11"Water Surface"

Fig. 11: Velocity distribution as contour lines in x-y Plane at level 2" Above the Bed"

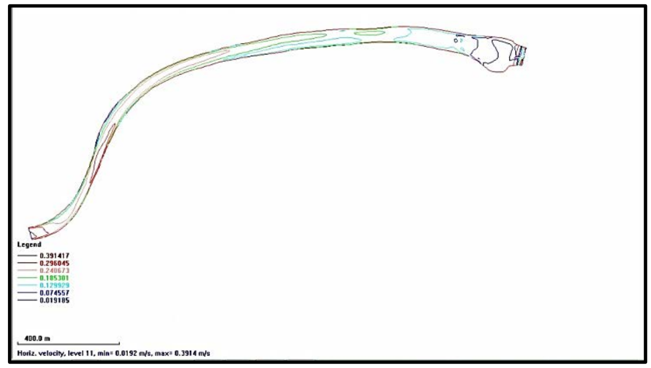

Fig. 12: Velocity distribution as contour lines in x-y Plane at level 11"Water Surface"

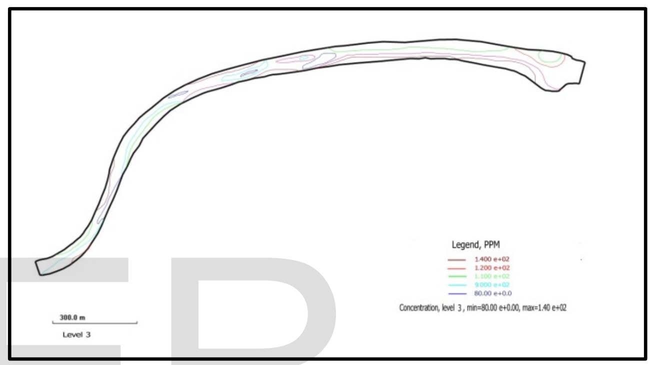

Fig.13: Sediment Concentration Profile at Deferent Levels (selected level 3) near bottom

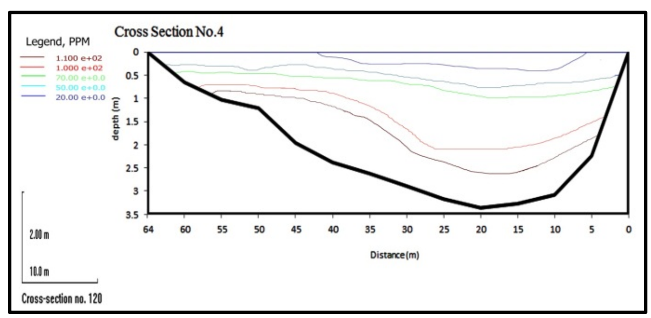

Fig. 14: Sediment Concentration Distribution as Contour Lines for section No. 4

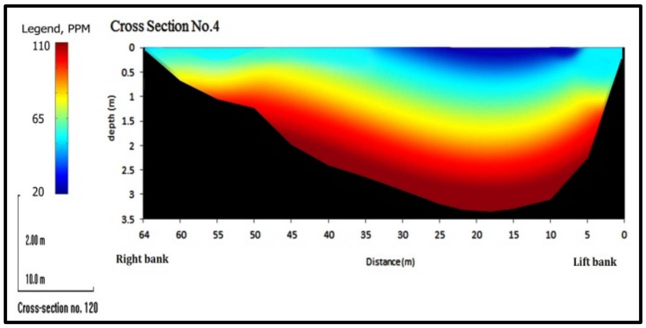

Fig. 15: Sediment Concentration Distribution as Gradient Colors at cross-section No. 4 by Tecplot360 software

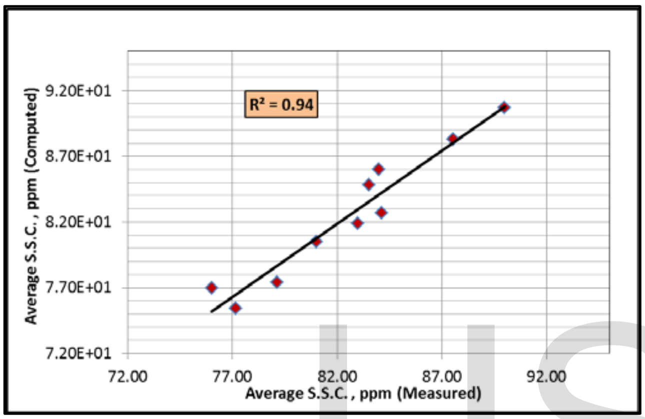

Fig. 16: Average S.S.C. Verification for All Sections

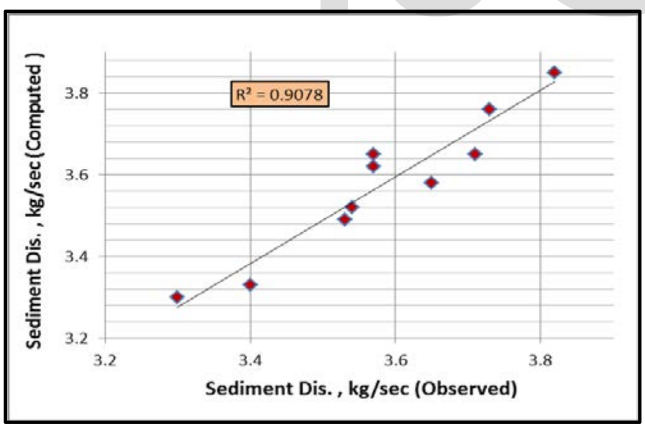

Fig. 17: Average S.S. Discharge Verification for All Sections

9 Conclusions

This study presents the development of the numerical model SSIIM .The study examined model results with respect to the those observed in the field in order to determine whether the numerical model (SSIIM) is able to predict sediment distribution in the study reach or not. The simulated results show SSIIM is able to make more reliable predictions and is therefore a useful tool for river, environmental and sedimentation engineering.

Based on the results obtained in this study ,the following points are concluded:

1. A good agreement was obtained between the measured and computed values of suspended sediment concentration at study reach in the three dimensions, with determination coefficients of 0.94.
2. A good agreement was observed between the measured and computed values of suspended sediment discharge at study reach in the three Dimensions, with determination coefficient of 0.9078.
3. The average suspended sediment discharge, for the observed data in the study region by field and laboratory works was (11.2878E+04) ton/year while the computed suspended sediment discharge in the numerical model SSIIM was (11.2740E+04) ton/year.
4. The SSIIM is one of the useful tools to predict the velocity distributions in three dimensions which gave good idea about the behavior of the flow velocities.
5. The analysis of sediment particle size showed that the bed material river is composed of sand , silt and clay , and a large portion of bed material is sandy material, with median grain size about (0.11) mm.

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