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Three-Dimensional Sediment Transport Modeling for the Upstream of Al-Amarah Barrage

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***Abstract*-Three-dimensional numerical computational fluid dynamics “CFD” computer program Sediment Simulation In Intakes with Multiblock option "SSIIM" was used to predict the flow field and sediment transported upstream Al-Amarah Barrage, south of Iraq. It solves the Reynolds-Averaged Navier–Stokes equations in three dimensions to compute the water flow and uses the finite-volume method as the discretization scheme. 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 results showed that the maximum velocities were inclined from the river center. Depending on the values of coefficient of determination, the verification showed good agreement between model results and observed data both for velocity distribution and suspended sediment concentration.**

Key Words - Suspended sediment, three dimensional modeling, CFD, SSIIM, ADCP, Al-Amarah Barrage.

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I. INTRODUCTION

Sediment is comprised of solid particles of mineral and organic material that are transported by water. In river systems the amount of sediment transported is controlled by both the transport capacity of the flow and the supply of sediment. The “suspended sediment load” refers to the fine sediment that is carried in suspension and this can comprise material picked up from the bed of the river (suspended bed material) and material washed into the river from the surrounding land (wash load). The wash load is usually finer than the suspended bed material. In contrast, the “bed load” comprises larger sediment particles that are transported on the bed of the river by rolling, sliding or saltation. Most rivers will transport sediment in each of these “load” forms, according to the flow conditions[1].

Since natural rivers are subject to constant erosion and sediment transport processes, the study of sediment transport mechanisms and transport capacity of stream flows is considerably important in river hydraulics and geomorphology. Sediment transport and sedimentation in rivers have serious consequences including formation of sediment bars and reduction of flood sediment transport capacity, affected dams lifetime and their reservoir capacity, severe erosion of hydro-mechanical facilities and damaging field and water structures, sedimentation at flow channels, and other hydraulic problems. Also, considering the principles of river material extraction and transported sediments by river flow in design of river structures, the study of various methods to predict river sediment transport rate seems to be necessary.

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

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

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.

The first term on the left side of the equation is the transient term. The next term is the convective term. The first term on the right-hand side is the pressure term. The second term on the right side of the equation is the Reynolds stress term. To evaluate this term, a turbulence model is required. 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 Navier-Stokes equations for turbulent flow in a general three-dimensional geometry are solved to obtain the water velocity. The *k*- ε model is used for calculating 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 equations are discretized with a control-volume approach. An implicit solver is used, also for the multi-block option. The SIMPLE algorithm (**S**emi-**I**mplicit **M**ethod for **P**ressure **L**inked **E**quations developed by Pantakar, 1980) is the default method used for pressure-correction.

The default algorithm in SSIIM neglects the transient term. To include this in the calculations the data set in the control file is used. The time step and number of inner iterations are given on this data set. For transient calculations it is possible to give the water levels and discharges as input time series.

II. THE TURBULENT KINETIC ENERGY (k)–EDDY VISCOSITY (ε) MODEL

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

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

k is turbulent kinetic energy, defined by:

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

k is modeled as:

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

Where P_k is given by:

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

The dissipation of *k* is denoted, 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 the above equations, the *C's* are different constants. These cannot be changed by the user.

The *k*- *ε* model is the default turbulence model in SSIIM.

III. THE KINETIC ENERGY (k) –SPECIFIC DISSIPATION RATE (ω) MODEL

The *k-ω* model was developed by Wilcox (2000). It is given by the following equations:

$$\nu_T = \frac{k}{\omega} \quad (8)$$

k is turbulent kinetic energy, similar to the *k*- *ε* model. *k* is modeled as:

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\sigma\, \nu_T \frac{\partial k}{\partial x_j}\right) + P_k - \beta^* k\omega \quad (9)$$

Where P_k is the production of turbulence. Similar to the *k-epsilon* model, instead of using the dissipation of *k* as the second variable, the model uses *ω*, which is the specific dissipation rate (units: seconds^{-1}). The equation for is modeled as:

$$\frac{\partial \omega}{\partial t} + U_j \frac{\partial \omega}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\sigma\, \nu_T \frac{\partial \omega}{\partial x_j}\right) + \alpha\frac{\omega}{k}P_k - \beta\omega^2 \quad (10)$$

The following values and formulas are used for the additional parameters.

$$\alpha = \frac{13}{25}\ ,\ \sigma = \frac{1}{2}\ ,\ \beta = \beta_0 f_\beta\ ,\ \beta^* = \beta_0^* f_\beta\ ,$$

$$\beta_0 = \frac{9}{125}\ ,\ \beta_0^* = \frac{9}{100}$$

$$f_\beta = \frac{1+70\chi_\omega^2}{1+80\chi_\omega^2}\ \chi_\omega = \left|\frac{\Omega_{ij}\Omega_{jk}S_{ki}}{(\beta\omega)^3}\right|\ \chi_k = \frac{1}{\omega^3}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j}$$

$$f_{\beta^*} = f(x) = \begin{cases} 1\ , & \chi \le 0 \\ \dfrac{1+680\,\chi_k^2}{1+400\,\chi_k^2}\ , & \chi > 0 \end{cases}$$

$$\Omega_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} - \frac{\partial U_j}{\partial x_i}\right) S_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)$$

The *k-ω* model often gives less turbulent diffusion than the *k-ε* model. This means it may over predict the size of recirculation zones, whereas the *k-ε* model often under predicts the recirculation zone length.

In SSIIM, the wall laws for the *k-ε* model are used also for the *k-ω* model. This is due to the easier inclusion of wall roughness.

IV. SEDIMENT FLOW CALCULATIONS

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[2].

Sediment transport is traditionally divided into bed load and suspended load. The suspended load can be calculated with the convection-diffusion equation for the sediment concentration, *c* (volume fraction in SSIIM):

$$\frac{\partial c}{\partial t} + U_j \frac{\partial c}{\partial x_j} + w\frac{\partial c}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\Gamma_T \frac{\partial c}{\partial x_j}\right) \quad (11)$$

The fall velocity of the sediment particles is denoted *w*. The diffusion coefficient, *Γ*, is taken from the *k-ε* model:

$$\Gamma_T = \frac{\nu_T}{S_c} \quad (12)$$

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

For suspended load, van Rijn (1984) developed a formula for the equilibrium sediment concentration, c_{bed}, close to the bed:

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$$c_{bed} = 0.015 \, \frac{d^{0.3}}{a} \frac{\left[\frac{\tau-\tau_c}{\tau_c}\right]^{1.5}}{\left[\frac{(\rho_s \rho_w)g}{\rho_w v^2}\right]^{0.1}} \quad (13)$$

The sediment particle diameter is denoted d, 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, v is the viscosity of the water and g is the acceleration of gravity. The empirical parameters in the equation (0.015, 1.5 and 0.3) may be changed by using the *F 6* data set in the control file.

The sediment concentration from Eq. (13) will be fixed in the cell closest to the bed. For time-dependent computations, it is also possible to use an algorithm that converts the concentration from the formula into a sediment entrainment rate. This is done by giving *F 37 2* in the control file.

The decrease, K, in critical shear stress for the sediment particles as a function of the sloping bed was given by:

$$K = \frac{\sin\varphi \cos\alpha}{\tan\theta} + \sqrt{\left(\frac{\sin\varphi \cos\alpha}{\tan\theta}\right) - \cos^2\varphi\left(1-\left(\frac{\tan\varphi}{\tan\theta}\right)^2\right)} \quad (14)$$

The angle between the flow direction and a line normal to bed plane is denoted α. The slope angle is denoted φ and θ is a kind of angle of repose for the sediment. θ is actually an empirical parameter based on flume studies. The factor K was calculated and multiplied with the critical shear stress for a horizontal surface to give the effective critical shear stress for a sediment particle.

In addition to the suspended load, the bed load, q_b, can be calculated. Van Rijn's formula for bed load is used:

$$\frac{q_b}{D_{50}^{1.5}\sqrt{\frac{(\rho-\rho)g}{\rho}}} = 0.053 \, \frac{\left[\frac{\tau-\tau_c}{\tau_c}\right]^{2.1}}{D_{50}^{0.3}\left[\frac{(\rho-\rho)g}{\rho v^2}\right]^{0.1}} \quad (15)$$

The empirical parameters in the equation (0.053, 2.1, 0.3 and 1.5) may be changed by using the function data set in the control file.

The bed form height, Δ, is calculated by van Rijn's equation (1987):

$$\frac{\Delta}{d} = 0.11\left(\frac{D_{50}}{d}\right)^{0.3}\left(1-e^{\left[\frac{\tau-\tau_c}{2\tau_c}\right]}\right)\left(25-\left[\frac{\tau-\tau_c}{\tau_c}\right]\right) \quad (16)$$

Where d is the water depth. The effective roughness is computed as (van Rijn, 1987):

$$k_s = 3D_{90} + 1.1\Delta\left(1-e^{\frac{25\Delta}{\lambda}}\right) \quad (17)$$

Where λ is the bed form length, calculated as $7.3d$.

Note that van Rijn's equations for bed form roughness were developed on mostly uniform sediments. For non-uniform sediments, the bed forms will be smaller.

Many of the parameters in the formulas given above can be changed by giving different parameters in the control file. If completely different formulas are to be used, this can be coded in the beddll.dll file[2].

V. REGION OF STUDY

The reach of study is a 4km part of Tigris River in Al-Amarah city (south of Iraq), Maysan province upstream Al-Amarah barrage. Its location is between latitudes 31.865°N and 31.850°N and longitudes 47.115°E and 47.155°E. Fig. 1 shows the study reach location

VI. VELOCITY MEASUREMENTS AND DISTRIBUTION

Twenty cross-sections; Fig. 2; were considered along the reach. At each section, bed elevation, top width, water level, area of cross sections, water velocity and discharge were measured using the ADCP technology. SonTek river tracker surveyor; Fig. 3 and Fig.4; and its software version 4.3 were used for this purpose. These measurements were tabulated in Table 1.

VII. SUSPENDED SEDIMENT CONCENTRATIONS

Suspended sediment concentration was measured and recorded to determine how much sediment is entrained in the stream flow. Depending on the desired degree of accuracy of the measurements, the number and location of sampling verticals should be selected. The common methods in use are given and briefly discussed by the Interagency Committee on Water Resources [3]. 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; three samples were taken at each vertical at three depths *0.8d, 0.6d* and *0.2d,* where *d* is the depth measured from water surface. A total of nine samples in each transect section. Every sample was marked with a sticker containing all information about the time, date and location. All field sampling were conducted between (1-9-2012 to 1-9-2013).

Once suspended sediment samples were collected, the samples were filtered using filter papers. The filters used had a pore size of 0.45µm and pre-dried for 15 minutes in

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an oven at 105 °C. The weight of the filter paper was measured prior to filtering. The amount of water being filtered was also measured. After the sediment was filtered out of the sample, the sediment and filter paper were placed on a dish and placed in an oven and baked for 24 hours at approximately 105 degrees Celsius to remove water from the sediment. After 24 hours the filter paper with sediment was removed from the oven and weighed. The mass of sediment could then be determined by subtracting the initial filter weight from the weight of the dried sediment and filter. Once the weight of the sediment and the volume of water filtered were determined, the following equation was used to calculate the suspended sediment concentration[4].

$$\textbf{Sediment Concentration}\ (Cs) = \frac{\textbf{Mass of Sediment}(M)}{\textbf{VolumeofWater}\ (v)} \quad (18)$$

Where Cs in *ppm or mg/l*; M in *mg* and v in *liter*.

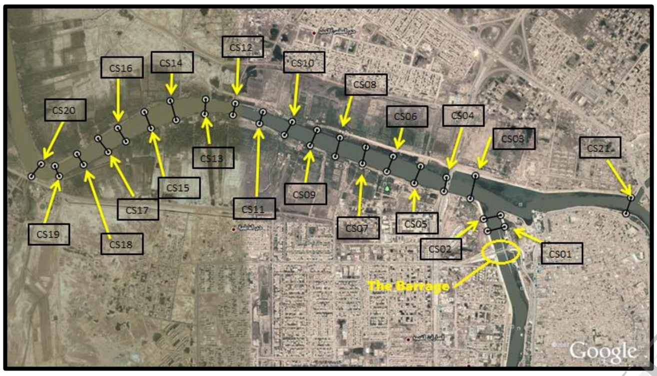

Fig. 2: Transect Sections Locations

Fig. 3: SonTek River Surveyor ADCP

VIII. BED MATERIALS SAMPLING

One bed material sample was taken for each section in study reach. The samples were taken using Van Veen's grab. For sample taking from the bottom surface the “Van Veen’s grab” is a very useful tool. It can be easily handled and gives in many cases quite good samples. During the descent to the bottom the two buckets are held in open position by the means of a hook. When the grab hits the bottom the tension on the hook is released and the hook is disengaged. When the line is hoist the buckets close automatically. The researcher had made a sampler similar to the former type to be used in this study.
Sieve analysis and specific weight were done for each bed sample, the results of these tests used as an input data in the model; Fig. 5. The procedure listed in ASTM D_{854} and AASHTO T_{100} was followed in the determination of specific gravity of bed sediments materials. The average value of specific gravity for all sections was (2.62).

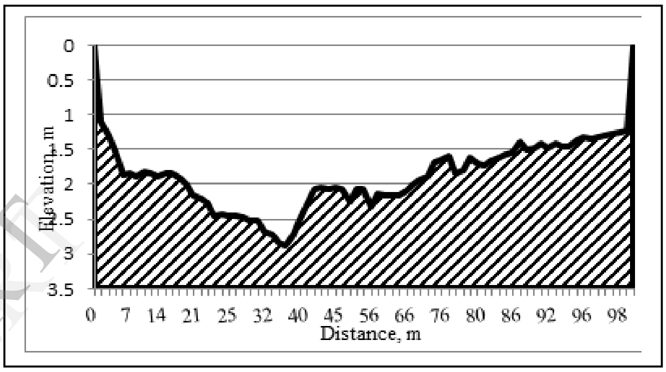

Fig. 4: Geometry of Section No.1 using the ADCP

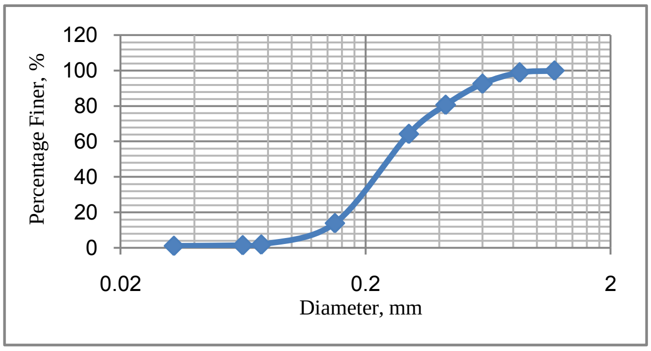

Fig. 5: Average Sieve Analysis for All Sections

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IX. SEDIMENT DISCHARGE IN STUDY REACH BY SSIIM

Suspended sediment transport rate (discharge) may computed from the following equation [4 and 5]

$$Q_s = C\,Q \qquad (19)$$

Where: Q_s = Sediment discharge (kg/sec).
C= Average concentration of suspended sediments (mg/lit).
$Q =$ Water discharge (m3/sec).

Average values of concentration of suspended sediments in each section (C), water discharge (Q) and sediment discharge (Q_s) were listed also in Table 1.

X. THE RESULTS FROM SSIIM

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

By means of scaled velocity vector. The upper layers have higher velocities compared to lower one, although uniformity is maintained layer wise. The maximum velocity is 0.563 m/s. The Fig. 6 and Fig. 7 below showed these distributions as velocity vectors and at different levels.

TABLE (1): HYDRAULIC PROPERTIES FOR ALL SECTIONS

Sec. No.	Depth (m)	Velocity (m/sec)	Area (m^2)	Q (m^3/sec)	A.S.C. (ppm)	Qs (kg/sec)
1	2.46	0.33	204.78	67.68	95.89	6.49
2	2.78	0.39	188.59	72.79	129.78	9.45
3	7.70	0.16	577.99	95.06	160.11	15.22
4	6.50	0.36	288.57	105.24	123.78	13.03
5	3.01	0.32	303.16	96.19	118.22	11.37
6	3.04	0.43	230.33	98.91	143.89	14.23
7	2.93	0.36	285.85	103.00	132.22	13.62
8	3.19	0.33	294.43	98.61	139.55	13.76
9	3.53	0.36	284.80	101.40	126.56	12.83
10	5.39	0.31	330.68	102.94	169.11	17.41
11	7.56	0.31	357.23	106.11	119.78	12.71
12	9.13	0.25	390.43	97.00	130.89	12.70
13	9.24	0.25	392.38	97.76	122.22	11.95
14	3.19	0.35	288.13	101.15	166.77	16.86
15	3.42	0.33	296.35	96.54	137.67	13.30
16	4.84	0.32	315.91	100.74	125.78	12.67
17	5.46	0.32	308.42	97.30	113.00	11.00
18	6.62	0.30	350.54	104.60	131.44	13.75
19	9.03	0.22	433.1	96.58	126.77	12.24
20	10.33	0.24	498.03	118.01	102.11	12.05
21	3.34	0.15	275.05	41.72	87.44	3.65

B. *Velocity Distribution in the Cross sections (Y-Z plane)*

The velocity vectors with scale at different cross sections are shown in Fig. 8. It depicts that the velocities are higher at upper part at the end of transition zone. The Flow achieves uniformity if the distributions of bed configuration are uniformity. These distributions will not still with change of bed. The maximum and minimum velocity is found near the surface depended on the depth of cross section. Fig. 9 showed the main flow velocity as contour lines.

XI. 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 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.

The results also showed that the software exhibits that suspended sediment concentration increase in the river section at the branch of river with barrage. Also the model showed that the deposition regions occur near the right bank of the river that is agreed with the satellite images; Fig. 10 and Fig. 11.

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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 Fig. 12 below showed the distributions of sediment in selected cross-sections.

XII. VERIFICATION 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 divided into two parts. The first part deals with flow calculation while the second part deals with sediment calculation as described in Fig. 13.

Each modeler and model reviewer will need to use their professional judgment in evaluating the calibration results. There are no universally accepted “goodness-of-fit” criteria that apply in all cases. However, it is important that the modeler make every attempt to minimize the difference between model simulations and measured field conditions.

According to the results, Fig. 14 indicate that there is fairly good agreement between measured and calculated velocities. One reason for the deviation between measured and calculated velocities can be due to some lack of accuracy in the measurements of the velocities and to the geometry of the reach. The software, estimate the bed-form between the consequent sections according to the data at these sections. This will lead to the geometry to be inexactly modeled.

The largest deviations between the measured and modeled velocities were found for velocity distribution at low discharge. This was due to the effect of bottom roughness on velocity distribution “Hydraulically rough flow”.

Figures (15, 16, and 17)showed the same trend as the velocities in the relation between the measured and the calculated sediment concentration and discharge.

Since, the boundary between bed-load and suspended load was defined as a layer with a maximum thickness of about 10 particles diameters in which the particles are transported as bed-load. According to van Rijn[6], this boundary will be collapsed or overlapped in low discharges but it has no effect in high discharges.

This was found to be the main reason behind the disagreement between the measured and calculated of the sediment concentrations.

The other reason for the deviation between measured and computed velocities and sediment concentration can 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 SSIIM model done the calculation at each node in three dimensions. The large numbers of node make the model more time consumption to solve Navier-Stock’s equations. At the same time the large number of grids makes the model more accuracy. The grids are further explained by Olsen (2011). In a structural three dimensional grid, each cell will have three indices, making it easy to identify grid locations.

The coefficient of determination, R^2, is the overall measure of the usefulness of a regression, the higher the coefficient of determination, the better the variance that the dependent variable is explained by the independent variable. In general it can be said that the results of verification are good[7, 8].

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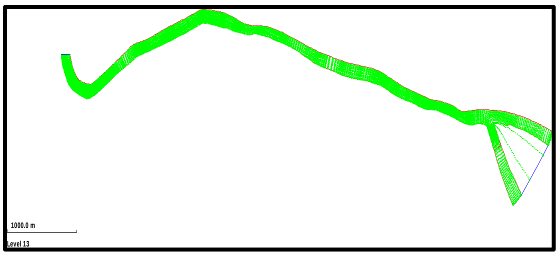

Fig. 6: Velocity Vector in x-y Plane at Level 2“Near the Bed”

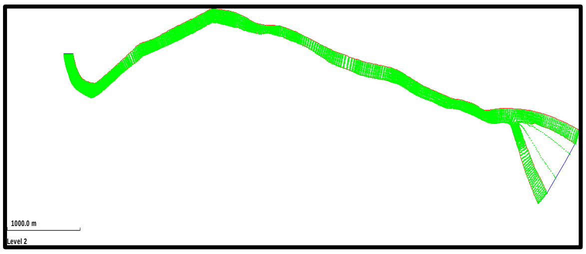

Fig. 7: Velocity Vector in x-y Plane at Level 2“Water Surface”

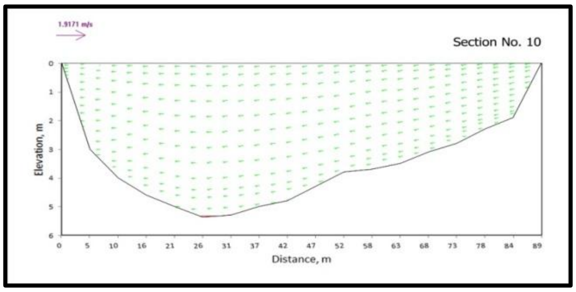

Fig. 8: Velocity Vector (secondary flow) in y-z Plane at Cross Section No. 10

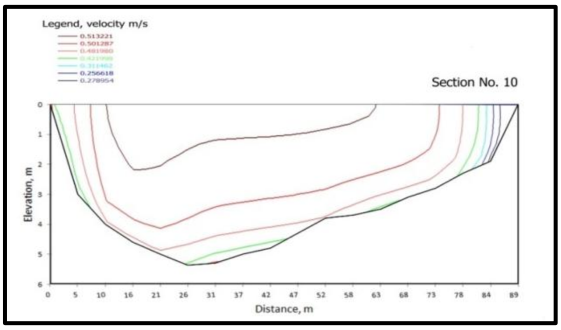

Fig. 9: Velocity Contour lines Distributions in y-z Plane at cross-section No.10

Fig. 10: The Location of Sediment Accumulation in the Right Bank at Branch to Barrage. (Google Image, at 2013)

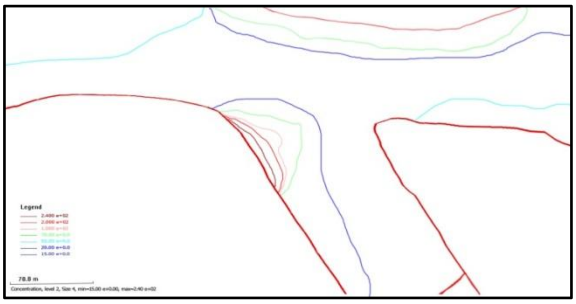

Fig. 11: The Location of Sediment Accumulation in the Right Bank at Branch to Barrage.
(By the SSIIM model)

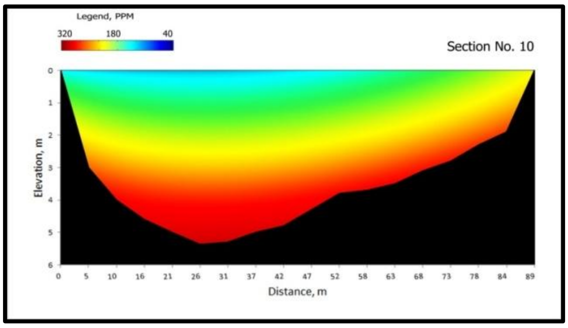

Fig. 12: Sediment Concentration Distribution as Gradient Colors at cross section No.10

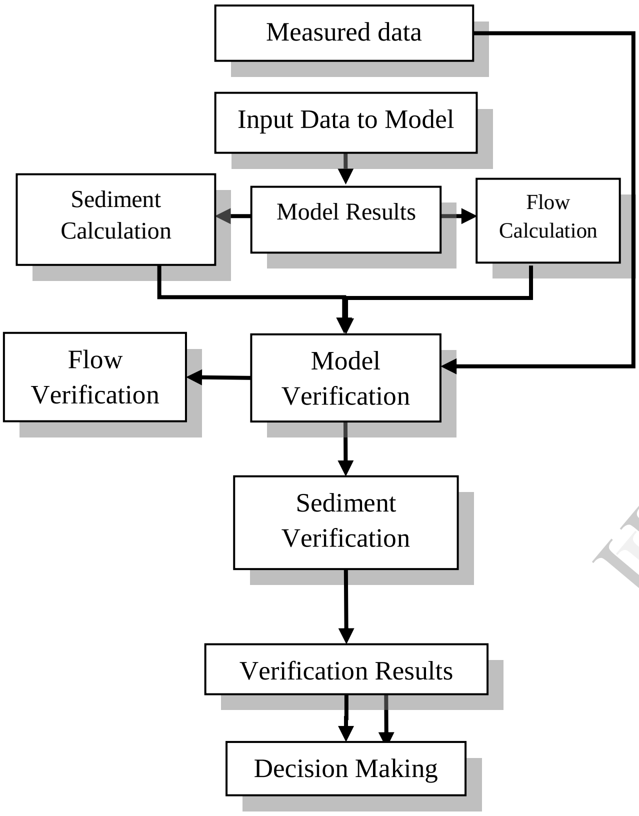

Fig. 13: Verification of a Numerical Model

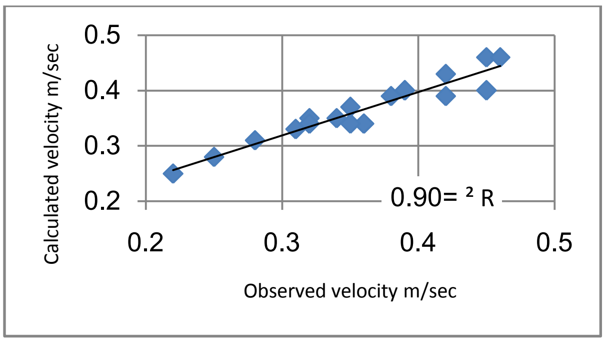

Fig. 14: Average Velocity Verification for All Sections

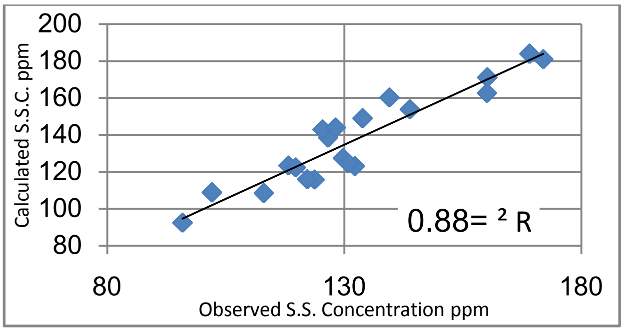

Fig. 15: Average S.S.C. Verification for All Sections

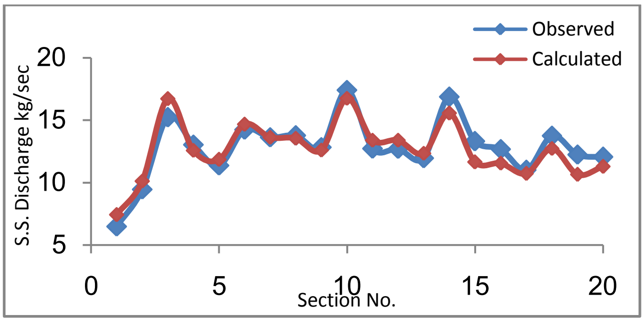

Fig. 16: Longitudinal S.S. Discharge Profile for All Sections

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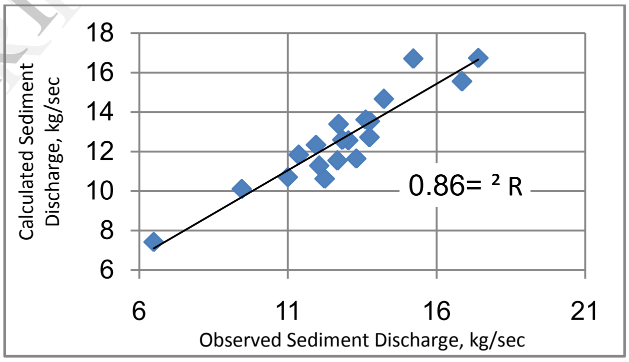

Fig. 17: Average S.S. Discharge Verification for All Sections

XIII. CONCLUSIONS

This study presents the development and comparison performed in the three dimensional numerical model SSIIM and a prototype. The study examined the model results with respect to 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.

According to the results obtained by this study, the following points are concluded:

1- A good agreement was observed between the measured and computed values of velocity at the study reach in the three dimensions, with determination coefficients of 0.90.
2- A good agreement was observed between the measured and computed values of suspended sediment concentration distribution at study reach in the three dimensions, with determination coefficient of 0.88.
3- 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 0.86.
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. Also it’s a good tool to predict sediment concentration and discharge.

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XIV. REFERENCES

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