SCOUR AT DAHSHOOR BRIDGE USING NUMERICAL MODELING AND NOVEL PIER SCOUR EQUATION

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ABSTRACT

In Egypt, concerns about bridge pier scour is one of the important reasons for limiting the increase of the current flow releases from High Aswan Dam (HAD) above the current maximum of 270 Million m^3/day. Higher flows might induce general scour at a bridge section if the bridge section is located in a scouring reach. In order to release higher flows than the current maximum, knowledge is required about how much total scour is expected around bridges built across the Nile River. Due to the importance of bridge pier scour, many investigators have worked on this critical subject but most of them have built their analysis on laboratory flume data that suffer from having simplified conditions and scale effects. When applying the existing empirical equations for predicting bridge pier scour to field cases, the scour depths are over-predicted which means increased construction costs. A new analytical equation for predicting pier scour is developed, Hafez 2004a, which are based on an energy balance theory. The developed equation expresses equilibrium bridge pier scour depth in terms of flow velocity, flow depth, bed sediment specific gravity, porosity and angle of repose, pier width over channel width ratio, and a momentum transfer coefficient. The equation has the advantages that it explains the physics of bridge pier scour in a direct way, relates the flow hydrodynamics to scour and most of all avoids the wide pier problem. For future high flows such as 350 Million m^3/day, it is only possible to obtain velocity through numerical models that simulate the flow hydrodynamics. Therefore, utilization is made to the WAVES two-dimensional (2D) numerical model, Hafez 2004b, for predicting the velocity, water depth and extracting the conditions at the pier for use in the pier scour equation.

The results of the combined application of a two-dimensional hydrodynamic model along with a pier scour equation and a one-dimensional morphological model revealed that the local pier, general and total scour at the three piers of Dahshoor bridge for maximum flow conditions of 350 Million m^3/day released from Assuite barrage are 7.97, 4.97, 4.92 m. It is recommended to consider the safe scour depth of 8.0 m for the western pier and 6.5 m for both the middle and eastern piers keeping in mind that the

present status of the river morphology in this reach should be preserved and not being changed by any future activities.

Key Words: Bridge Pier Scour, Sediment Transport

INTRODUCTION

When a bridge is built across an alluvial channel, the obstruction of the flow by the bridge piers induces higher velocities and vortices that cause scour of the channel bed around the piers. If this scour reaches the foundation level of the bridge piers, the bridge might collapse. Bridge pier scour is the leading cause of bridge failure. In Egypt, concerns about bridge pier scour is one of the important reasons for limiting the increase of the current flow releases from High Aswan Dam above the current maximum of 270 Million m^3/day. Due to high flood conditions that might occur at the High Aswan Dam, flows up to 350 Million m^3/day could be released from Aswan down to Cairo under emergency conditions. These higher flows constitute risks to bridges and other structures on the Nile River especially in narrow river sections where general scour is expected. General scour is dictated by the overall characteristics of the river reach between two control sections such as the reach between two barrages. Current practice of scour assumes that the total scour at a bridge is the algebriac summation of the local pier scour and the general scour.

In this study a new bridge on the Nile River is proposed at Dahshoor city located at 887.865 Km from Aswan, Fig. 1. The bridge has three piers crossing a width of about 350 m of the Nile River. The bridge span is 136 m separating the central pier from each of the eastern and western (side) piers. The Central (middle) pier length is 54 m while the two side piers are of 44.0 m length. The width of all the piers is 8.0 m with a sharp triangular upstream nose and trapezoidal downstream nose. It is required in this study to estimate the maximum possible scour at the bridge piers due to the maximum expected flows in this reach. The maximum possible flow is taken as 350 Million m^3/day.

PROBLEM DESCRIPTION

The problem to be solved herein consists of estimating both of the local pier scour dictated by the pier geometry shape and the general scour, if any, dictated by the overall conditions of the reach between two control sections. The total scour is then, simply the algebraic summation of these two types of scour. In knowing the amount of total scour the bridge piers foundations are designed accordingly with allowance for soil bed material to be removed equal to the maximum expected total scour.

RIVER REACH CONDITION

For the numerical simulation of the flow field at Dahshoor bridge, the boundaries of the river area at the Bridge is defined and divided into finite elements. Figure 1 shows the layout of the study area at Dahshoor bridge along with the location of the river bed surveyed cross sections by NRI. The figure shows the Nile channel flows to the north west direction but in a straight reach or section, free of meanders or islands or submerged sand bars. Eleven cross sections covering 1.2 Km of the river channel were surveyed with the bridge section located at CS No. 6 and reported in NRI 2003. Velocity measurements were taken at cross sections No. 3, 6, and 9 and also shown in NRI 2003. Though the river reach looks straight in planform, the surveyed cross sections show transverse bed slope which is usually found in curved river reaches. The western part of the river channel is deeper than the eastern part by about 3.0 m in some cross sections. This might cause strong cross currents even though the river reach is straight and free of meanders.

The average width of the river cross sections is around 350 m. The maximum flow discharge in the period from 1999 to 2000 was 181.3 Million m^3/day while the minimum flow was 29.2 Million m3/day. The maximum water level at the site is (19.89) m while the minimum one is 16.43 m, NRI 2003. The soil bed of the river is mostly medium sand with D50 ranging between 0.29 mm to 0.74 mm. The water is almost free of suspended sediments as sediment concentrations are below 50 p.m.m. The measured velocity at flow of 44.65 Million m^3/day downstream the nearby Assiut Barrage ranged between 0.32 m/s to 0.59 m/s. These rather high values of the velocities considering that the discharge is small signal that the river reach is relatively narrow with the effect of having higher velocities and tendency for scour. At cross sections No. 3 and 9 the velocity is higher at the deeper western side of the cross section than at the eastern shallow side.

THE 2D NUMERICAL MODEL STRUCTURE

In order to obtain the velocity and water depth at the bridge piers, two dimensional numerical modeling is used. A numerical model called WAVES (**WA**ter **V**elocity **E**levation **S**imulation), Hafez 2004b, is constructed to simulate the current flow conditions in rivers and lakes systems. The model is two-dimensional (horizontal resolution) with a finite element mesh or grid. A diffusive type approximation is used along with the finite element method which solves numerically the system of governing differential equations. The proposed **WAVES** 2-D numerical model is based on applying the conservation of mass and momentum concepts in two-dimensions that describe sufficiently the movement of water in lakes and channels.

1.Construction of the Finite Element Mesh

The study area comprised the reach between the most upstream and downstream velocity cross sections, namely between cross sections No. 3 and CS No. 9 with a distance of 478 m. The area was divided into 9640 elements as shown in Figure 2. Each element has four nodes, thus the finite element mesh of the study area has 9949 nodes. The elements were concentrated around the bridge piers and in areas where high variations are expected.

The cross section passing through the center line of the bridge (CS No. 6) is taken as the Y axis (i.e. at which X = 0) while the origin point (the point with {0,0} coordinates) is located at the intersection of the Y axis with the eastern bank as shown in Figure 2. The upstream CS No. 3 is located at X = -258 m while the Downstream CS No. 9 is located at X = 220 m. The eastern pier longitudinal axis is located at Y = 39 m, the central pier longitudinal axis is at Y = 175 m, while the western pier axis is located at Y = 311 m.

2. River Bed Model Representation

A bed level interpolator included in the WAVES model interpolated the bed levels given by the cross sections from 3 to 9. It is seen that the western part of the river channel is deeper than the eastern part. There is a scour hole at CS No. 4 at the eastern part which disappears at CS No. 5, i.e. before the bridge location.

3. Initial and Boundary Conditions

The boundary conditions to the WAVES model consist of specifying upstream unit depth discharges (at CS No. 3) and downstream water level (at CS No. 9). The unit depth discharges were taken equal to the measured depth-averaged velocity at CS No. 3 times the local depth while the downstream water level was taken equal to the measured water level at CS No. 9 which was (16.93) m, NRI 2003. The initial water level was taken as (16.95) m at the rest of the nodes but after running the model, all the water levels, except at the downstream boundary, are recomputed. The Manning's roughness coefficient was taken as 0.06 which reflects the fact that the period of measurements corresponded to the low flow period where roughness is expected to be high and the existence of dune bed features increase the hydraulic roughness.

4 Results of the Validation Run

The model is run for the data corresponding to measurements taken in December 2002. The inflow from Assuite Barrage was 44.65 Million m^3/day and the water level in the area was around (16.93) m. Though the bridge was not yet constructed at this time, it is included in the finite element grid. The effect of the bridge on the hydraulic conditions is only local and affecting few meters around the bridge axis, i.e., only the velocity at CS No. 6. Figure 3 shows the longitudinal water surface profile through the channel centerline for the model calculated flow of 43.3 Million m^3/day. The upstream model prediction of the water level was 16.97 while the measured water

level was (16.97) m, therefore good agreement between the model and field measurements is achieved in predicting the water surface profile.
The model predicted discharge is obtained via integration of the velocities over the exit cross section (CS No. 9). The model yielded a value of 43.3 Million m^3/day compared to measured flow of 44.65 Million m3/day downstream of Assuite barrage which constitutes good agreement. Figure 4 shows the model predicted velocities at the inlet cross section (CS No. 3) where comparison of the longitudinal velocities reveal reasonable agreement with slight over-prediction. It is noted from the figure the existence of cross or lateral velocities in the order of + or - 0.15 m/s which is expected due to the strong transverse bed slope at this area. Figure 5 shows vector plot of the velocity field for the whole study area and at the inlet and around the bridge piers.

HIGH FLOW APPLICATION

The high flow run includes releasing a flow of 350 Million m^3/day from Assuite barrage passing through the bridge site. The dwonstream boundary condition water level at CS No. 9 is taken as (20.20) m according to the results of applying the NERVE 1D hydraulic model in a prevoius study, NRI 2000. The Manning's roughness coeffifients at the grid points were taken as 0.05 utilizing the fact that the Manning's roughness coeffient is proportional to the negative power of the discharge.
Figure 6 shows longitudinal water surface profile at Dahshoor Bridge through the river axis. The upstream water level is (20.45) m and with a downstream boundary water level of (20.2) m , the difference between the upstream and downstream water levels amounts to 0.25 m compared to 0.04 m in the validation run. This indicates increase of the water surface slope in the reach and the consequent increase in the velocity field as the energy slope has increased.

Figure 7 shows the resulting longitudinal velocity distribution across the channel width at the inlet section (CS No. 3) where the velocity maximum shifted to the middle and reached 2.0 m/s. Most of the cross section had velocities over 1.5 m/s which indicates intensive energy levels and more power of the stream for transporting bed sediments. Figure (8) shows the velocity distribution of the longitudinal and lateral directions at the bridge axis (along CS No. 6). From the figure it is apparent that the lateral flow is almost nill while the longitudinal velocity are over the 1.5 m/s level across most of the cross section. The maximum longitudinal velocity appears at the western pier with value of about 2.3 m/s. The velocity at the other two piers (the middle and the eastern one) is around 1.75 m/s which is less by about 30% than the western pier. Comparing Figures 7 and 8, it is apparent that the section maximum longitudinal velocity is higher at the bridge section than at the inlet section by about 23% which indicates the effect of the bridge on the velocity maxima. Figure 9 shows the velocity distributions at the exit section (CS No. 9) where the longitudinal velocity maximum dropped to 2.0 m/s shifted to the western side indicating the vanishing effect of the bridge at this section.

Table 1 below shows the location and values of the maximum velocities in the vicinity of the western pier.

Table 1 Velocities and Depths at the Western Pier for Flow of 350 Million m3/day

Point	X_Coordinate (m)	Y_Coordinate (m)	Longitudinal Velocity (m/s)	Lateral Velocity (m/s)	Resultant Velocity (m/s)	Water Depth (m)
1	-17.36	315.8	2.584	0.425	2.619	9.56
2	+17.36	315.8	2.547	-0.726	2.648	9.54

From Table 1 it is apparent that at the point with coordinates (+17.36 m, 315.8 m) the resultant velocity is maximum with value of 2.648 m/s. This point is located at the end of the western pier. At point 1 in Table 1 (point –17.36 m, 315.8 m) the longitudinal velocity is higher than point 2 while the lateral velocity is less. It is expected that severe scour occurs around these two points.
Table 2 shows the values of the velocities and water depth at the vicinity of the central pier.

Table 2 Velocities and Depth at the Middle Pier for Flow of 350 Million m^3/day

Point	X_Coordinate (m)	Y_Coordinate (m)	Longitudinal Velocity (m/s)	Lateral Velocity (m/s)	Resultant Velocity (m/s)	Water Depth (m)
1	-22.235	182.2	1.958	0.258	1.98	6.6

Tables 1 and 2 show that the velocities and depth are less at the central (middle) pier than at the western pier at which the bed level is deeper.

Table 3 shows the velocities and depth at the vicinity of the eastern pier for flow of 350 Million m^3/day. It is noted that the velocities are higher at the eastern pier than at the central pier but the water depth is less. The velocity maximum occurs near the front of the eastern pier.

Table 3 Velocities and Depth at the Eastern Pier for Flow of 350 Million m^3/day

Point	X_Coordinate (m)	Y_Coordinate (m)	Longitudinal Velocity (m/s)	Lateral Velocity (m/s)	Resultant Velocity (m/s)	Water Depth (m)
1	+17.36	34.2	2.001	0.438	2.06	5.95

LOCAL SCOUR ESTIMATION

An energy balance, Hafez 2004a, theory assumes that at the equilibrium geometry of the scour hole, the work done by the attacking fluid flow upstream the bridge pier is equal to the work done in removing the volume of the scoured bed material. In other words the energy contained in the fluid flow attacking the bridge pier is converted to energy consumed in removing or transporting the bed material, thus forming a scour hole. When all the flow energy is consumed in transporting the sediment out of the scour hole, scour ceases and the scour hole becomes stable and at its maximum scour-depth.

The work done by the fluid flow of the horizontal jet coming from upstream the bridge pier in the stagnation symmetry plane can be expressed as

$$\frac{\rho V_X^2 h d \eta^2}{\left(1-\frac{b}{B}\right)^2} \frac{(h+D_s)}{2} \qquad (1)$$

where ρ is the fluid (water) density, V_x is the longitudinal flow velocity of the jet attacking the bridge in the direction normal to the pier, h is the water depth, d is the bed material diameter, η is a transfer coefficient of the horizontal momentum into a vertical momentum in the downward direction, b is the pier width, B is the channel width in case of one pier or the bridge span or pier centerline to centerline distance in case of multiple piers and D_s is the maximum or equilibrium scour depth.

The work done in removing the bed material from the scour hole is equal to:

$$\frac{1}{6}\left(\frac{D_s^3}{\tan\Phi} d\right)(1-\theta)(\gamma_s-\gamma) \qquad (2)$$

where ϕ is equal to the bed material angle of repose, θ is the bed material porosity, γ_s is the bed material unit weight and γ is fluid unit weight.

Under the condition of equal work at the equilibrium conditions (or maximum scour) equations 1 and 2 are equated and after some manipulation yield:

$$\left(\frac{D_s}{h}\right)^3 = \left(\frac{3\tan\phi}{(S_G-1)(1-\theta)}\right)\left(\frac{1}{(1-\frac{b}{B})^2}\right)\left(\frac{\eta^2 V_x^2}{g h}\right)\left(1+\frac{D_s}{h}\right) \qquad (3)$$

where S_G is the sediment specific gravity. Equation 3 expresses the equilibrium bridge pier scour depth in terms of the local velocity, local flow depth, bed material specific gravity and porosity, bed material angle of repose, pier width over channel width ratio, and a momentum transfer coefficient. The Froude number can be easily made to appear in Eq. 3. The equation has the advantages that it explains the physics of bridge pier scour in a direct way, relates the flow hydrodynamics to scour and most of all does not suffer from the wide pier problem. Equation 3 is a cubic non-linear equation.

Though a closed form expression for the scour depth could be obtained, a few iterations could be used instead to solve for the scour depth.

CALCULATION OF THE MAXIMUM LOCAL SCOUR

Now that the velocity and water depth field are calculated the application of Eq. 3 is possible for the calculation of the maximum local pier scour depth. The data needed in Eq. 3 include the bed sediment angle of repose, porosity and specifiec gravity. The angle of repose is taken as 40 degrees, the porosity as 0.4 and the sediment specific gravity as 2.65. The gravitational acceleration is taken as 9.81 m/s^2. As each pier has 8.0 m width, the three piers total width is 24 m and with 4 m extra width for each pier for the sheet piles around each pier during the construction phase, the total obstructed width at the bridge section is 36 m , i.e. b =36 m in Eq.3. The river channel width at the bridge section is taken as 350 m. From Table 1, the maximum velocity at the western bridge pier is 2.66 m/s while the flow water depth is 9.54 m. Substituting these values into Eq. 3 yields

$$\left(\frac{D_s}{h}\right)^3 = \frac{3\tan 40°}{(2.65-1)*0.6} \frac{1}{(1-\frac{36}{350})^2} \frac{2.65^2}{9.81*9.54} (1+\frac{D_s}{h}) \qquad (4)$$

Eq. 4 can be simplified to

$$\left(\frac{D_s}{h}\right)^3 = 0.237 \ (1+\frac{D_s}{h}) \qquad (5)$$

Eq. 5 is non-linear equation which when solved by trail and error yields

$$\frac{D_s}{h} = 0.75 \qquad (6)$$

For a depth, h, equal to 9.54 m, Eq. 6 yields maximum scour depth at the western pier of Dahshoor bridge equal to 7.2 m. Therefore, it can be concluded that the maximum local pier scour for a flow of 350 Million m^3/day at the western pier of Dahshoor bridge is 7.2 m.

Applying the data for the middle and eastern piers from Table 2 and 3 in the same manner as was done for the western pier when using Eq. 3, the pier scour depths are 4.52 m at the Central pier and 4.4 m at the eastern pier. Table 4 shows the local pier scour depths for the three piers of the Dahshoor Bridge for flow of 350 Million m^3/day.

Table 4 Local Pier Scour at Dahshoor Bridge for Flow of 350 Million m^3/day

Pier Location	Distance of the Pier Axis from the East Bank (m)	Local Pier Scour depth in (m)
Western Pier	311	7.20
Middle Pier	175	4.52
Eastern Pier	39	4.40

It is clear from Table 4 that the local pier scour is the highest at the western pier followed by the middle pier and at last comes the eastern pier. This is due to the fact that the bed level is deepest at the western pier and hence the water depth is highest at the western pier. As the shear stress is proportional to the water depth, it follows then that the shear stress acting on the river bed is the highest at the western pier. As scour is proportional to the acting shear stress on the river bed, the local scour depth should be the highest at the western pier, then at the central pier and finally at the eastern pier.

GENERAL AND TOTAL SCOUR ESTIMATION

To estimate the general scour at Dahshoor bridge a one-dimensional morphological model called NERVE (Hafez and El Kady 2001) was applied to the whole reach from Assuite Barrage down to Delta barrage which covres a distance of about 400 Km. Cross sections surveyed by NRI in 1997 were used for representing the river bed where the total number of cross sections amounted to 45 cross sections. The high flow of 350 Million m^3/day was simulated for 30 days as seen in Fig. 10. Initially the flow at Assuite barrage was 170 Million m^3/day which is raised to 350 Million m^3/day during the first 18 days in incerements of 10 Million m^3/day. The total simulation time was 67 days. The downstream water level boundary condition at Delta barrage followed the shape of the discharge hydrograph as seen in Fig.11. Fig. 11 shows the water level was raised from a level of (16.32) m to (17.5) m in the first 18 days, then the (17.5) m level continued for 30 days after which the falling stage started.

Fig. 12 shows the cross section near Dahshoor bridge located at Km 887.3 while the bridge is located at Km 887.865 which is very close. The figure reveals the tendency for scour at this bridge section because it is narrow with width of about 400 m. The general scour depths at the western, middle and eastern piers are 0.77 m, 0.45m and 0.52 m, respectively as interpolated from
Table 5.

Table 6 shows the values of the local pier scour, general scour and total scour at Dahshoor bridge. It can be concluded from Table 6 that the total scour depth at the western pier could be taken as 8.0 m while for both the midlle and eastern piers a value of 5.0 m can be taken. It should be rememebered that these values are based on the river bed surveyed in 1997 and 2002 and conditions that were prevailing at this time.

Future changes to the river course either natural or artificial could cause significant change in the river morphology affecting he bridge section. For example, the present analysis depends on the fact hat the 2002 river bed is deeper at the western part of the cross section which is evident from the surveyed river bed but future dredging or construction of new structures on the Nile river course might cause shifting of the river bed so that the eastern part becomes deeper while the western part becomes shallower. If this happens the scour depths will be greater at the eastern pier than at the western pier. Therefore, extereme caution must be taken when viewing the results of this analysis and extra safty measures in the design of the bridge should be undertaken. For example, the maxium scour value of 8.0 m should be applied to all the three piers to be in the safe side.

Table 6 Values of Pier, General and Total Scour at Dahshoor Bridge

Pier Location	**Distance of the Pier Axis from the East Bank (m)**	**Local Pier Scour depth in (m)**	**General Scour Depth in (m)**	**Total Scour Depth in (m)**
Western Pier	311	7.20	0.77	7.97
Middle Pier	175	4.52	0.45	4.97
Eastern Pier	39	4.40	0.52	4.92

CONCLUSIONS AND RECOMMENDATIONS

1. The results of the combined application of a two-dimensional hydrodynamic model along with a pier scour equation and a one-dimensional morphological model revealed that the local pier, general and total scour at the three piers of Dahshoor bridge for maximum flow conditions of 350 Million m^3/day released from Assuite barrage are as given in the following table:

Pier Location	**Distance of the Pier Axis from the East Bank m**	**Local Pier Scour depth in m**	**General Scour Depth in m**	**Total Scour Depth in m**
Western Pier	311	7.20	0.77	7.97
Middle Pier	175	4.52	0.45	4.97
Eastern Pier	39	4.40	0.52	4.92

2. It is recommended to consider the safe scour depth of 8.0 m for the western pier and 6.5 m for both the middle and eastern piers keeping in mind that the present status of the river morphology in this reach should be preserved and not being changed by any future activities. The scour depth should be measured from the current lowest bed level at the bridge axis.
3. Construction Manual for the bridge should be produced in order to follow up the carried out work.
4. Construction should be carried out such that only one pier is constructed in order to avoid significant constriction of the river.
5. Fenders should be constructed for each pier to protect the piers from the navigational units.

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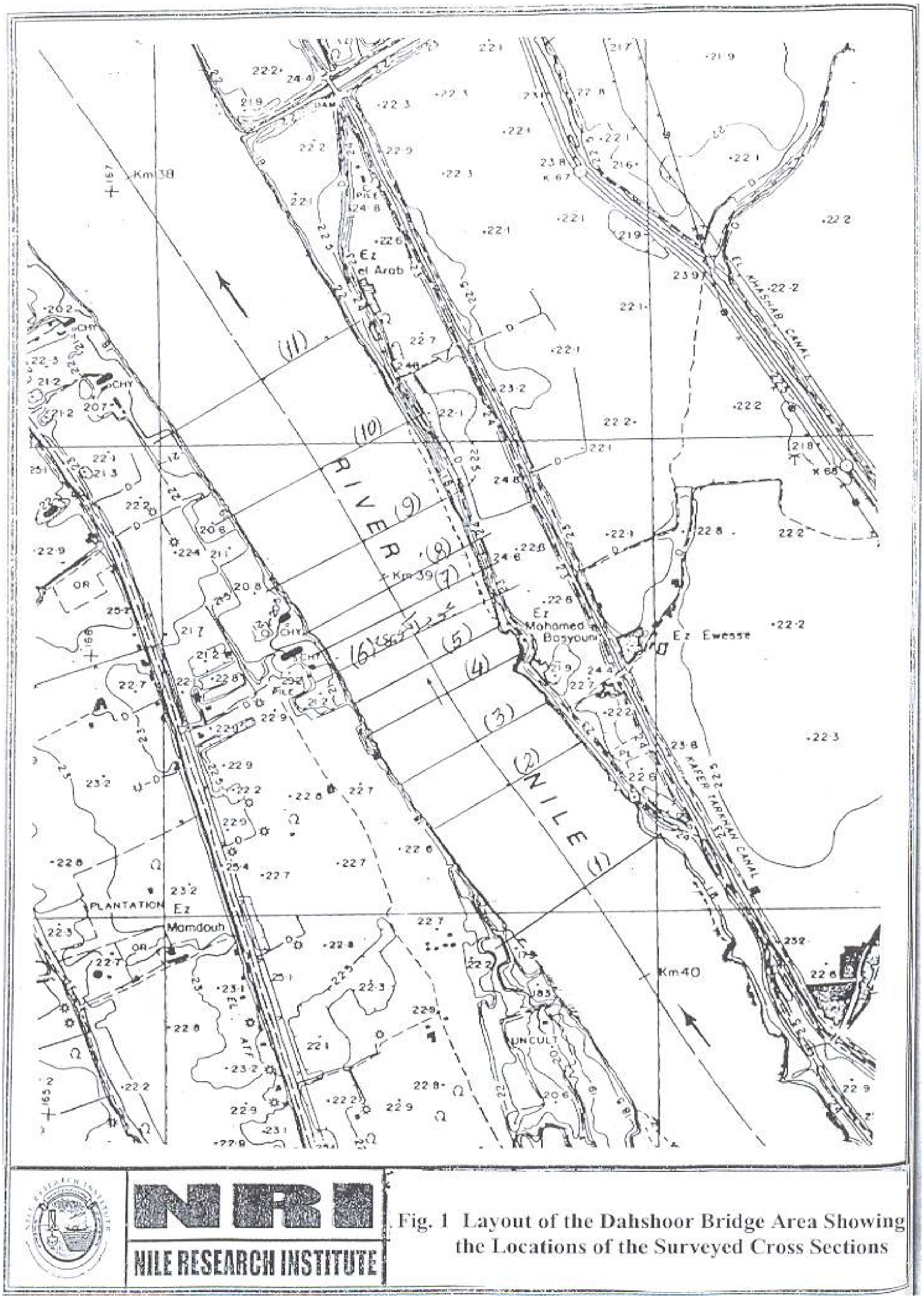

Figure 1: Layout of the Dahshoor bridge area showing the locations of the surveyed cross sections

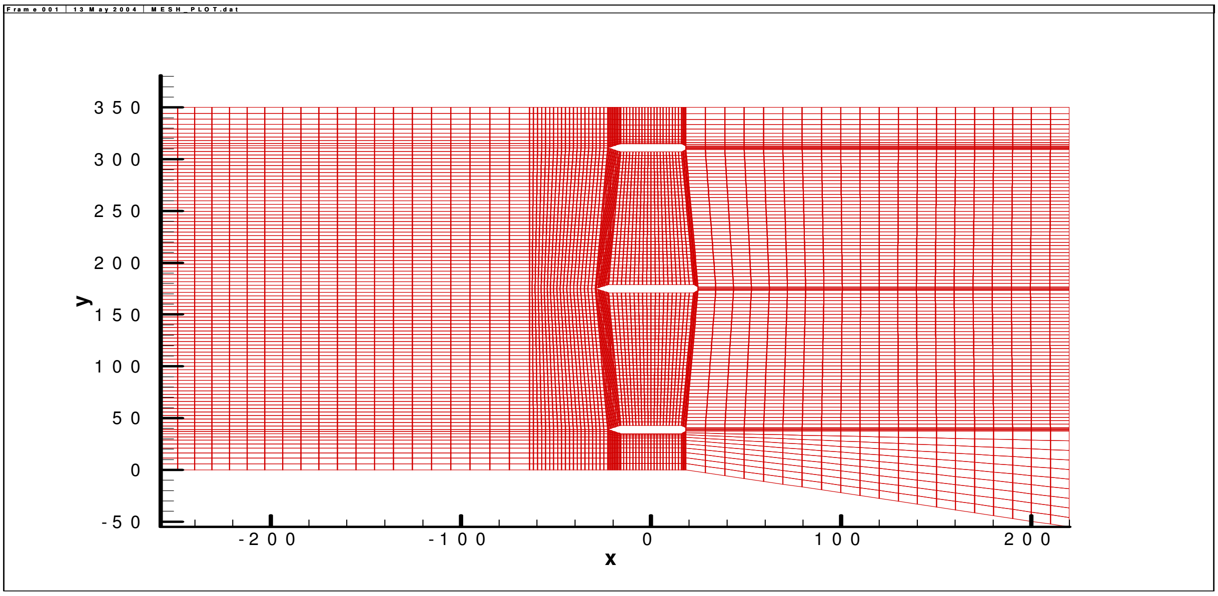

Figure 2: The Finite Element Mesh for the Area Around Dahshoor Bridge (Flow from Left to Right)

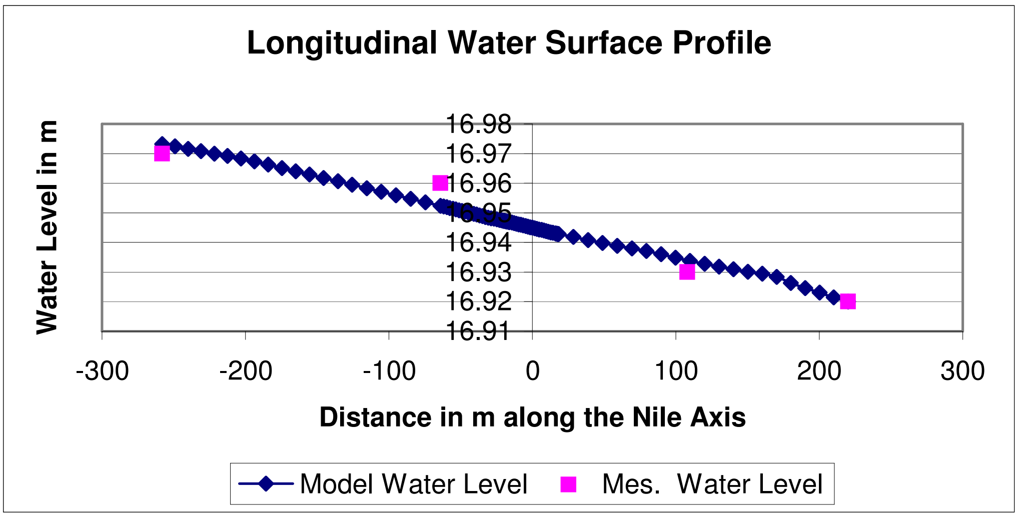

Figure 3: Comparison Between the Model and Measured Water Levels for $Q = 43.3$ Million m^3/day

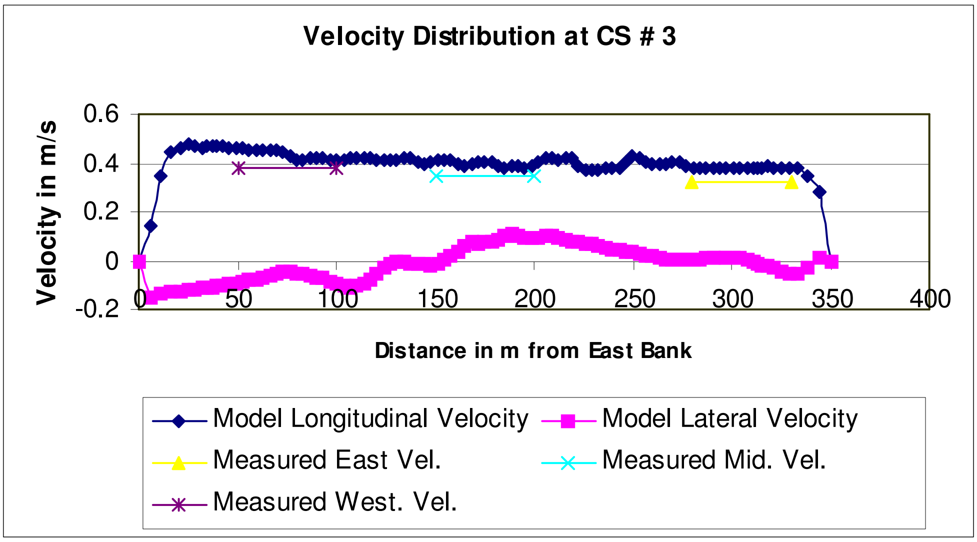

Figure 4: Comparison Between the Model and Measured Longitudinal Velocity at CS # 3 for Q = 43.3 Million m^3/day

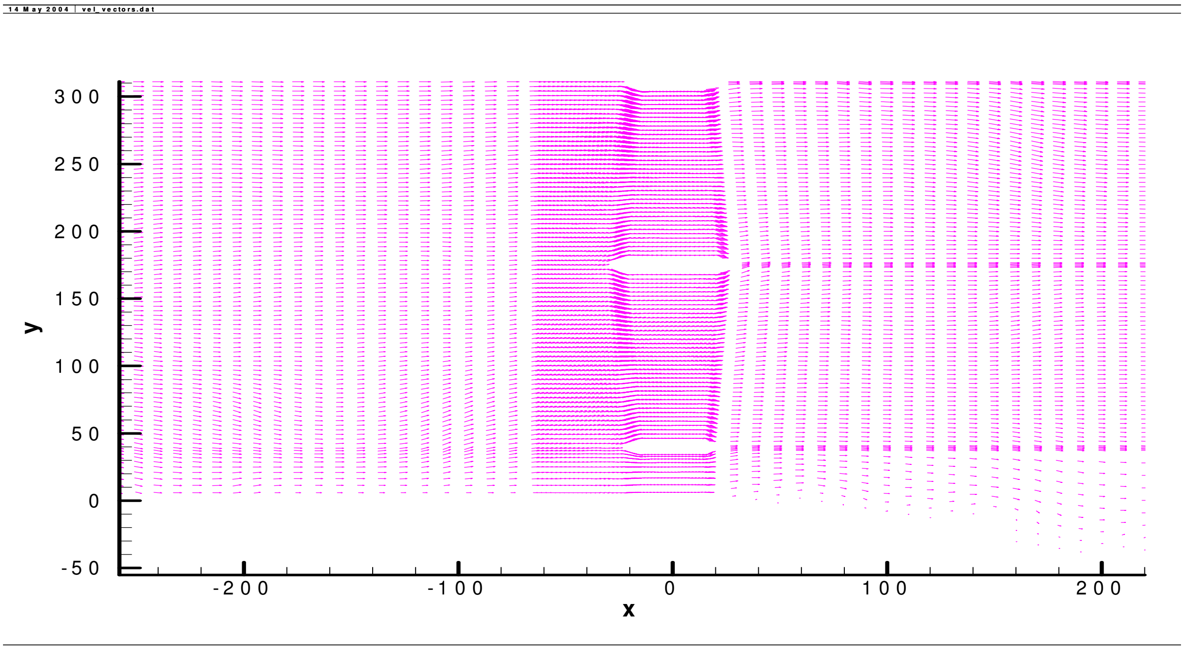

Figure 5: 2D Vector Plot of the Velocity Field at the Area of Dahshoor Bridge for Q = 43.3 Million m^3/day

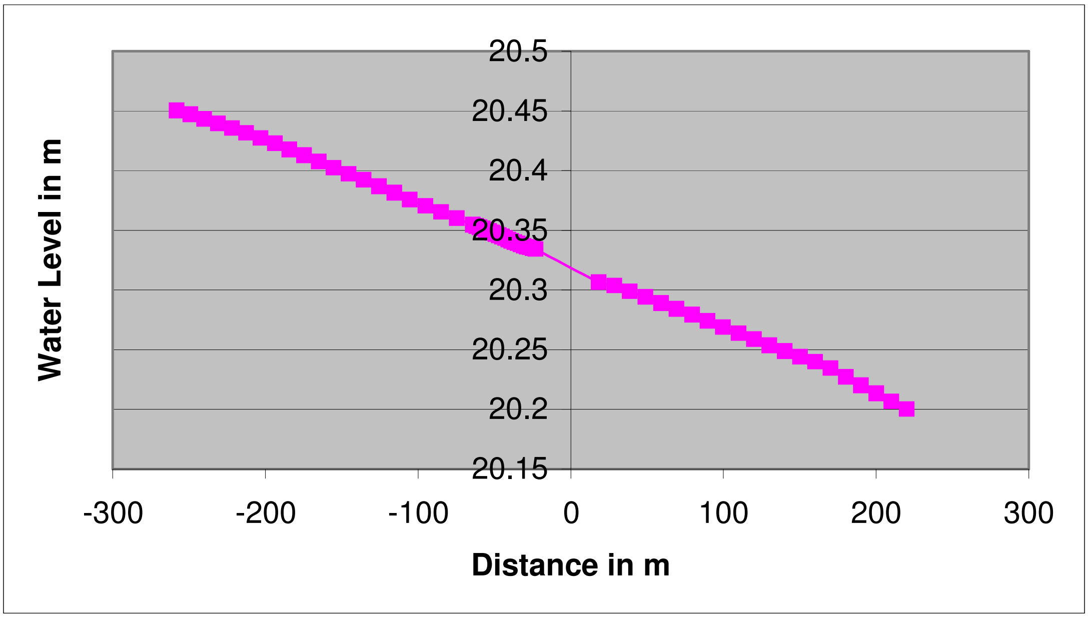

Figure 6: Longitudinal Water Surface Profile at Dahshoor Bridge for Flow of 350 Million m^3/day

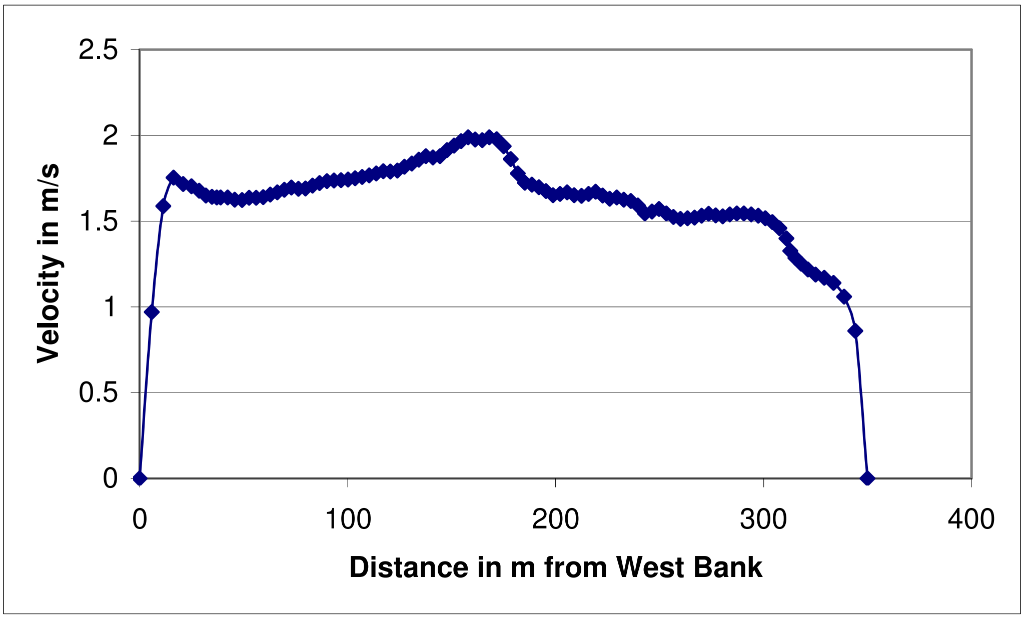

Figure 7: The Longitudinal Velocity at CS# 3 for Flow of 350 Million m^3/day

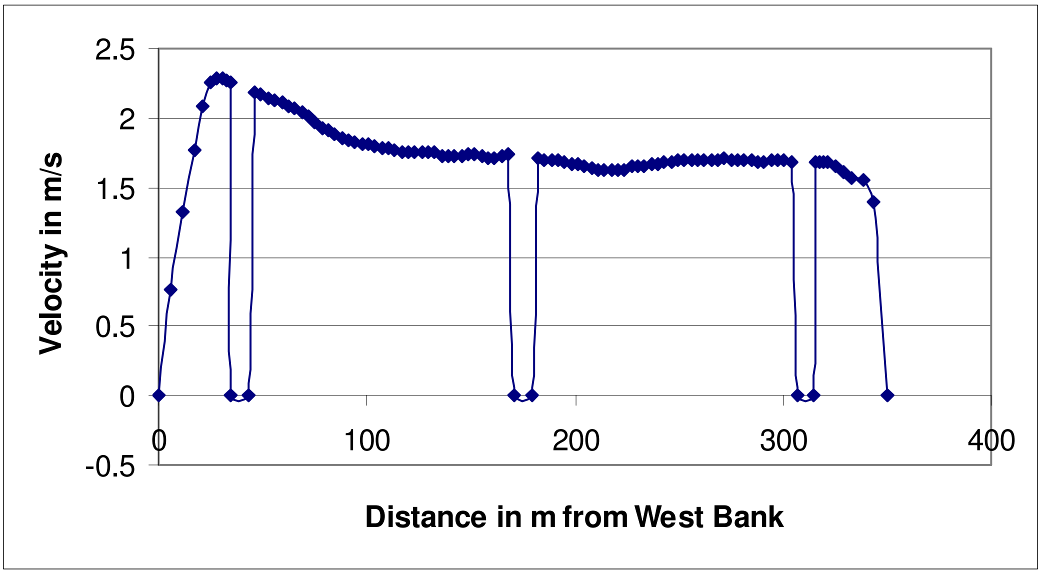

Figure 8: The Longitudinal Velocity at the Bridge Axis (CS # 6) for Flow of 350 Million m^3/day

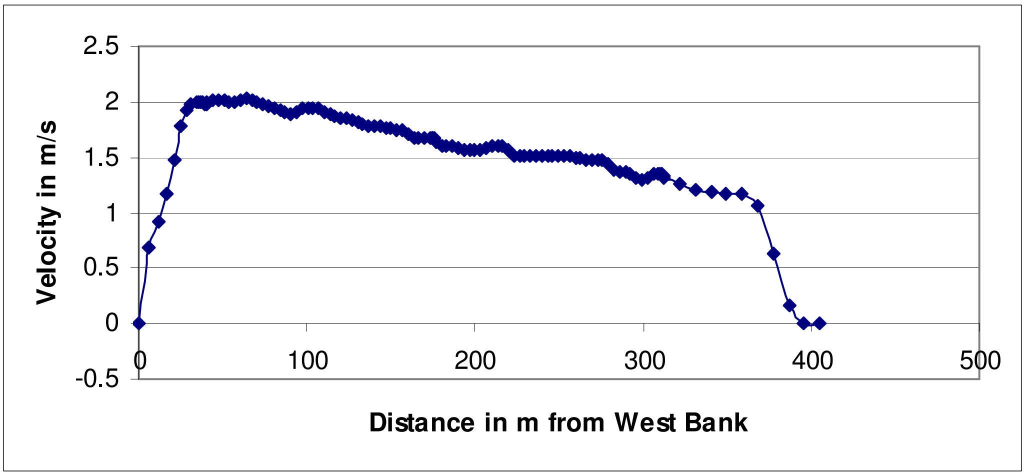

Figure 9: The Longitudinal Velocity at CS # 9 for Flow of 350 Million m^3/day

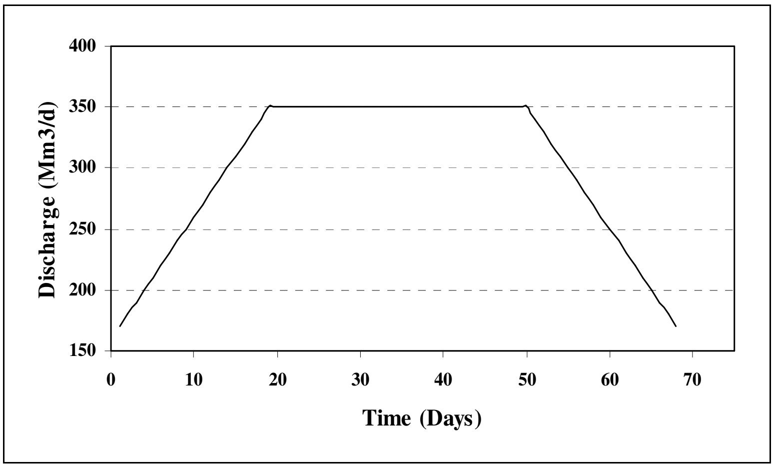

Figure 10: Flow Hydrograph Downstream Assuite Barrage for High Flow Run

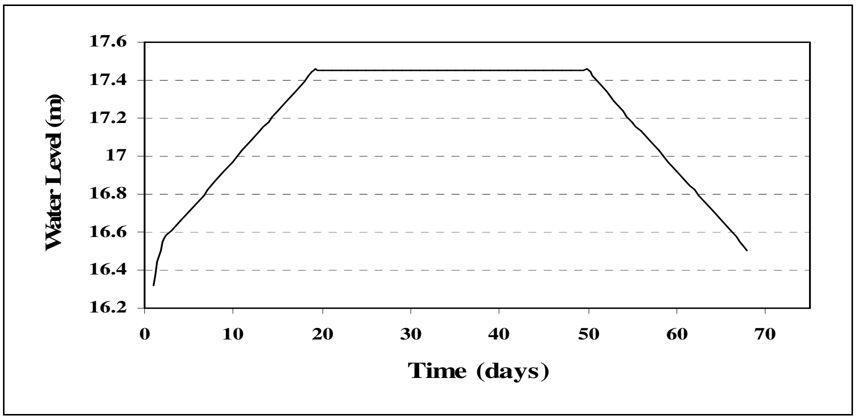

Figure 11: Stage Hydrograph Upstream the Delta Barrages for the High Flow Run

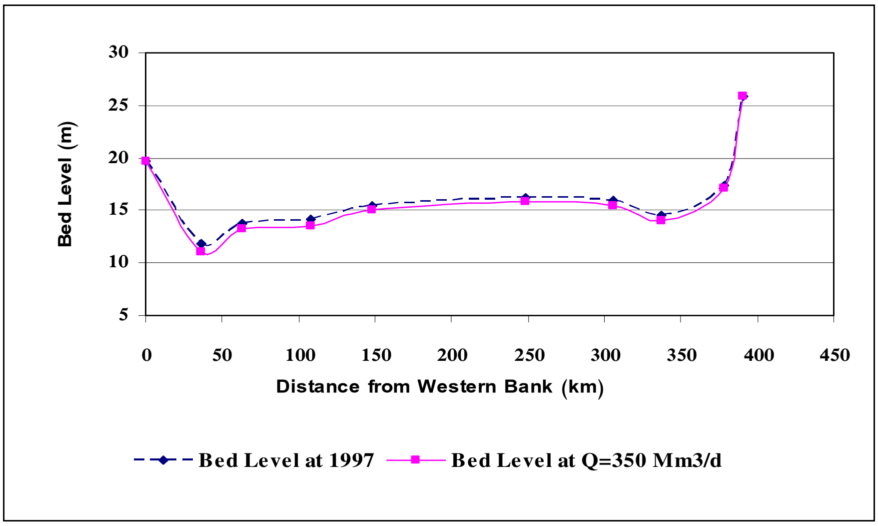

Figure 12: General Scour at Dahshoor Bridge due to Flow of 350 Million m^3/day