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Flood-induced scour in the Nile by modified operation of High Aswan Dam

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Due to climate-change it is anticipated that the hydrological regime of many river basins is gradually changing. This requires a revision of operation rules of the affected hydropower, flood control and water-supply reservoirs, as well as the impacts of modified operation on the downstream reach. The Lake Nasser Flood and Drought Control (LNFDC) Project has addressed these issues for the Nile River and Lake Nasser in Egypt. As part of this project the impact of man-induced increased flood releases on scour in the lower Nile River have been investigated. In the past 30 years, since Nile flows are regulated by the High Aswan Dam, the river channel has changed to such an extent that risk of damage by scour and flooding has increased significantly. Most relevant risks are related bridge-pier scour, scour at barrages, and bank erosion. Predictions based on analytical methods and scale model experiments show at three barrages protection is needed to deal with possible scour. Also bank erosion at a number of locations requires initial protection works.

I. INTRODUCTION

In historic times the sand-bed of the Nile River in Egypt was sensitive to local scour phenomena such as bank erosion (notably bend scour), scour at bridge piers, and scour downstream of the main barrages in the river (located along the Nile as shown in Figure 1). Scour holes of tens of meters, and annual shifts of bank lines of hundreds of meters have been reported. However, after construction of High Aswan Dam (HAD) the flood discharges in the lower Nile River in Egypt have significantly been reduced. Due to the absence of these floods the local-scour phenomena also have become inconsiderable.

HAD is by far the most important structure to regulate the water flow of the river Nile in Egypt. This dam is a rock fill dam with a total length of 3,600 m and a maximum height above the Nile bed of 111 m. The amount of water stored behind the dam at a level of 183 m+MSL (the maximum in case of an emergency situation) is 169 BCM (BCM = 10^9 m^3), which is about twice the average annual yield of the River Nile at Aswan. The length of the reservoir is 500 km with an average width of 12 km.

If the reservoir level exceeds a height of 178 m, water is spilled to the Toshka depression (see Figure 1). This occurred the last four years year after year, to an average annual amount of 10 BCM. The Toshka canal and spillway were designed to convey some $250 \cdot 10^6$ m^3/day (i.e., 250 MCM/day = 2,900 m^3/s) at a level of 182.7 m. Its capacity amounts only 150 MCM/day at a level of 182 m. Plans have been made to upgrade the Toshka canal by deepening and widening it. At present the water release to the Nile is limited to 270 MCM (3125 m^3/s) as more discharge is believed to cause serious degradation of the bed of the river Nile and may endanger the stability of the riverbanks, bridge piers and other structures. Furthermore, because the discharge through the Nile has been low since HAD was put into operation, at various locations constructions have been built in the floodplain. Hence, flood damage may be experienced if the Nile conveys a too large discharge.

Figure 1 Overview of water resources system of Egypt, showing the main barrages and irrigation canals

In the year 2001 Egypt indeed experienced a flood from the River Nile for the first time since the construction of the High Aswan Dam. Although the discharges were not more than 270 MCM/d, the flood caused damage in the lower parts of Egypt. The vulnerability for flood damage at these relatively low peaks lies mainly in the changed land use resulting from the perception of the people that the Egyptian Nile is fully under control. The inflow in Lake Nasser was however so high for a number of consecutive years, that Lake Nasser operation had to be adjusted.

Considering the expected climate change, the changes in the upstream catchment and change of land use and water resources demands downstream, a need for reconsidering the operation of HAD was born. In the year 2005 the National Water Resources Plan (NWRP) was approved by the Cabinet. In this plan an outlook for the management of the water in Egypt up to the year 2017 is presented. It gives a strategy to develop the country's water resources and to cope with many of the effects of the growing Egyptian economy on the natural resources system. One of the proposed measures was to look into the operation of Lake Nasser.

These developments form the stage for the Lake Nasser Flood and Drought Control (LNFDC) Project. The aim of the project is to strengthen the capability of the Ministry of Water Resources and Irrigation (MWRI) to analyse these developments and to answer some key-questions. One of the key questions relevant for scour in the Nile has been: should excess water be spilled over the Toshka spillway or should excess water be released to the Nile?

This release will increase flood discharges up to 400 MCM/day for a period of several weeks through the lower Nile reach. The most important damage caused by these manmade floods is expected to be caused by local scour, and particularly scour at bridge piers, barrages and erosion of river banks. As a subcomponent of the LNDFC project vulnerable locations have been identified, and predictions have been made using semi-analytical approaches as well as a scale model study. In the following sections the approach for scour assessment is presented for separate scour phenomena in the Nile River.

II. LOCAL SCOUR IN THE NILE IN THE PRESENT AND THE PAST

Local scour at the hydraulic structures located across the Nile River constitutes a major concern. The two main types of hydraulic structures on the Nile River are bridges and barrages. In table II an overview of the main barrages in the Nile is given. It can be seen that most barrages are constructed and designed in pre-HAD conditions, except for the New Esna barrage.

The morphological processes in the Nile River have significantly changed by the change of regime after construction of HAD. It can be seen in Figure 2 that the reservoir fully controls the Nile flows; the high flows during August and September are completely eliminated and maximum discharges are now limited to 270 MCM/day, i.e. less than 1/3 of the earlier peak values. Note that bankfull discharge of the lower Nile is in the order of 600 MCM/day, and therefore the discharge is completely conveyed through the main channel.

TABLE I.
GENERAL DATA ON RIVER NILE STRUCTURES

Name of structure	Construc-ted	Chain-age (km)	Design Head (m)
Aswan Dam	1898-1902	0	33.0
Esna Barrage	1906-1908	166.65	5.0
New Esna Barrage	1990-	167.85	7.0
Nag Hammadi Barrage	1927-1930	359.45	4.5
Asyut Barrage	1898-1902	544.75	4.3
Mohamed Ali Delta Barrages -Damietta -Rosetta	1843-1863	 952.92 952.92	 2.0 2.0
Delta Barrages -Damietta -Rosetta	1936-1939	 953.20 953.76	 3.8 3.8
Zifta Barrage (Damietta)	1901-1903	1,046.7	4.0
Damietta Dam (Fariskour)	1985-1988	1,161.0	2.2
Idfina Barrage (Rosetta)	1951	1,159.0	2.7

source: River Regime of the Nile in Egypt, NRI, 1992

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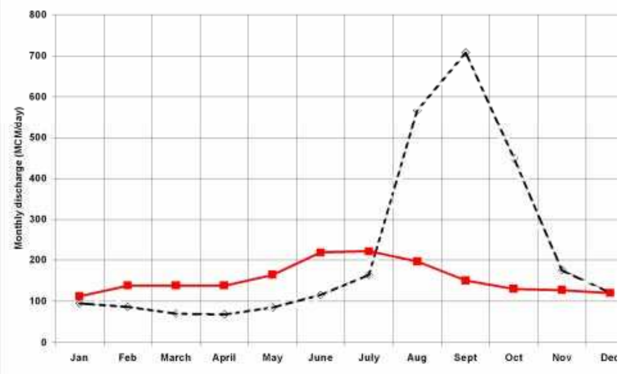

Figure 2 Average monthly flow of the Nile at Aswan before (dashed line) and after (drawn line) the construction of HAD (data 1938-1962 and 1969-1988)

Furthermore the HAD has a huge effect on the transport of sediments. The supply of sediment is interrupted as sediment from upstream is captured by the reservoir, and the transport capacity of the lower Nile has been reduced because of the reduced discharges. For instance in 1967 in Dongola a peak concentration of 8900 mg/litre was measured, whereas downstream Aswan the peak value was less than 100 mg/litre. Downstream Aswan the mean annual suspended load transport prior to HAD amounted 129 Mt/yr against 2.27 Mt/yr after 1967, which is only 2% of the original value. Under the post HAD conditions further downstream the mean annual suspended load transport doubles almost to 4.23 Mt/yr. If the bed-material transport is assumed as 50% of the suspended load (NRI,

[6]), then there is a difference of nearly 3 Mt/yr between the upstream and downstream reaches, which would mean, in absence of other sources, bed degradation. Part of the difference may be due to some influx of wind-blown sediment: the river is in direct contact with the desert in the reaches 1 and 2 over a total length of 43 km. Assuming that these influxes are small (wind direction is generally north, i.e. parallel to the river), the data would lead to an average bed degradation of 4 mm/yr. In the first 5 years after the implementation of HAD the bed levels in the reaches 1 to 3 dropped by 40 to 50 cm, whereas no changes occurred downstream Asyut. Thereafter, in sections the bed level drop continued and in other sections rose.

Since the construction of the HAD the number of islands in the river between Aswan and Cairo reduced drastically from 150 to 36 in 1989, due to infilling of secondary channels. In 1988 along 567 km of 2033 km of riverbanks between Aswan and Cairo bank protection in the form of revetments and spur dikes was available. Bank erosion took place along some 242 km of riverbanks.

Below the HAD the Nile flows in a northerly direction over a distance of 950 km before the river bifurcates at the apex of the Nile Delta into the Damietta and Rosetta branches to reach the Mediterranean Sea respectively 250 and 240 km further downstream (see Figure 1). From Aswan to the head of the Nile delta, a distance of 943 km, the river bed drops from 79 m to 11 m+MSL. This implies an average bed slope of 7.2 cm/km. It appears though that the bed slope increases from less than 5 cm/km in the upper reaches to over 8 cm/km further downstream. The bed slope of the Damietta branch is about 6 cm/km and of the Rosetta branch 8 cm/km. The top width of the river varies from 640 in the upper reaches to 540 towards Cairo. The flow depth ranges between 4 and 6 m under the present river regime.

The bed material consists of medium to fine sands with D_{50} (median grain size) values of 0.31, 0.25, 0.42 and 0.43 mm. and D_{90} of 0.80, 0.70, 0.90 and 0.90 mm. in the first four river reaches respectively. With this type of fine sediment the river bed is very susceptible to local scour. Scour can be quite significant if no protection is provided. In the following sections is shown what the impact of increased discharges will be.

III. LOCAL SCOUR AT BRIDGE PIERS

Various empirical relations for bridge pier scour have been applied, e.g., Shen et al. [7], Colorado State University (CSU) [2], Jain and Fischer [5] and others. In addition, the applicability of a newly developed analytically based equation by Youssef Hafez [4] from Hydraulics Research Institute (HRI) based on an energy balance theory is investigated. Because the latter has been derived for Nile data, it is obvious that the new equation by Hafez performs best to the bridges across the Nile and is therefore used in the final estimation of scour depths. The equation of Hafez expresses equilibrium bridge scour depth, and reads:

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

in which

B = the channel width (if one pier) or bridge span (if multiple piers at equal distances)
b = obstruction width or pier width
D_s = equilibrium scour depth
g = gravitational acceleration
h = approach water depth
S_G = the sediment specific gravity
u = local flow velocity
ϕ = the bed material angle of repose,
η = a coefficient reflecting momentum transfer,
ε = the bed material porosity,

The factor η has been found to vary between 0.56 and 1.00 (based on tests). The parameter must be calibrated to reduce the inherent uncertainty of this equation. For the hydraulic parameters the 1D hydraulic model, using the SOBEK modeling system [8], has been applied.

The local scour has been observed around bridge piers of the following bridges:

1. El-Tahrir Bridge at Cairo (built pre-HAD). Contains 7 piers with intermediate of distance 50 m. Current stable scour-hole depth is about 3.5 m. Predicted scour depth with formula of Hafez [4] for 270 MCM/d is 1.73 m, and for 400 MCM/d is 2.35 m.

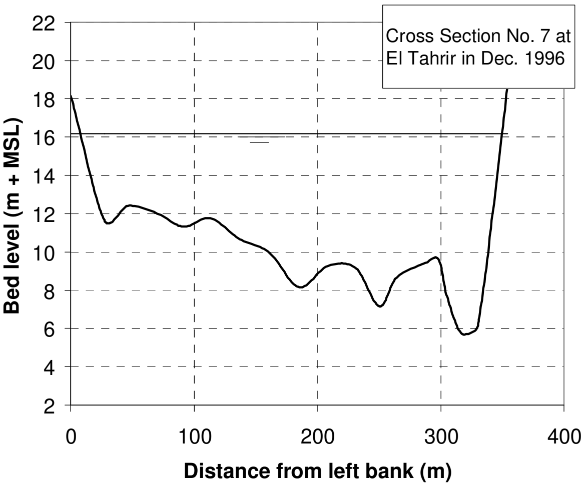

Figure 3 Cross Section No. 7 at El Tahrir showing scour holes at the Bridge Piers

2. Imbaba Bridge at Cairo (built pre-HAD). Contains 8 piers with intermediate of distance 65 m. Current stable scour-hole depth is about 5.25 m. Predicted scour depth with formula of Hafez [4] for 270 MCM/d is 1.76 m, and for 400 MCM/d is 2.41 m.
3. El Marazek Railway Bridge at Marazek near Helwan (built pre-HAD). Contains 8 piers with intermediate of distance 90 m. Current stable scour-hole depth is about 6 m. Predicted scour depth with formula of Hafez [4] for 270 MCM/d is 2.10 m, and for 400 MCM/d is 2.95 m.
4. Edfina Railway Bridge at the end of Rosetta Branch. Contains 4 piers with intermediate of distance 80 m. Current stable scour-hole depth is between 4 and 9 m.

Predicted scour depth with formula of Hafez [4] for 270 MCM/d is 2.13 m, and for 400 MCM/d is 4.34 m.

5. Desouk Railway Bridge at Rosetta Branch. Contains 6 piers with intermediate of distance 70 to 35 m. Current stable scour-hole depth is about 2 m. Predicted scour depth with formula of Hafez [4] for 93 MCM/d (Rosetta) is 1.25 m, and for 261 MCM/d is 2.24 m.
6. Rahmania Railway Bridge at Rosetta Branch. Contains 2 piers with intermediate of distance 60 m. Current stable scour-hole depth is about 2 m.
7. Zefta Railway Bridge at Damietta Branch. Contains 4 piers with intermediate of distance 35 to 70 m. Current stable scour-hole depth is about 5 m. Predicted scour depth with formula of Hafez [4] for 59 MCM/d (Damietta) is 1.93 m, and for 139 MCM/d is 3.58 m.
8. Mansoura Railway Bridge at Damietta Branch. Contains 4 piers with intermediate of distance 35 to 70 m. Current stable scour-hole depth is about 4 m. Predicted scour depth with formula of Hafez [4] for 59 MCM/d (Damietta) is 1.35 m, and for 139 MCM/d is 2.57 m.
9. Kafr el-Zayat Railway Bridge at Rosetta Branch (see Figure 4). Contains 4 piers with intermediate distance of 35 to 70 m. Current stable scour-hole depth is about 4.5 m. Predicted scour depth with formula of Hafez [4] for 93 MCM/d (Rosetta) is 2.26 m, and for 261 MCM/d is 3.95 m.

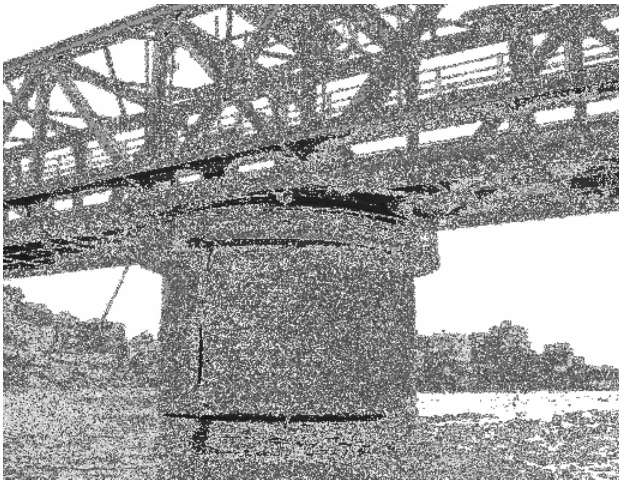

Figure 4 Central (largest circular) pier of Kafr el-Zayat railway bridge

From this list it can be observed that the predicted scour depths are generally smaller or in some cases equal to the current scour depths. It is concluded that the local scour around bridge piers at the bridges listed above is in a stable condition under the current flow conditions as well as for discharges up to 400 MCM/day at HAD.

IV. LOCAL SCOUR AT BARRAGES

Scour at barrages occurs downstream of the gates. The Nile barrages are designed to with-stand local scour under working conditions that are less severe than the expected flood scenarios in LNFDC Project. On basis of computations and scale model tests it is assessed whether scour can become a threat for the barrages.

Before the construction of High Aswan Dam (HAD) in 1964 all barrage gates during the flood season were completely opened with the barrage acting as a bridge section with constriction scour only expected. In the rising period of the flood, scour occurred while in the falling period filling of the scoured holes occurred by the flood sediment laden water. In the present situation, after HAD, the observed scour holes are due to conditions where the water is almost clear of sediment. Scour is presently resulting from high velocity jets either from high head difference on the barrage or high unit width discharge due to gate operation schemes. Maximum scour occurred when most of the discharge was forced in a few gates of the barrage causing a highly concentrated jet attacking the bed protection and natural-river-bed. This type of scour is not related to the discharge but rather to improper gate management.

The water jet is controlled by the head difference on the barrage, gate dimensions (width and height), stilling basin characteristics and the downstream water level. When gates are operate such that the whole discharge is concentrated to a few gates, the downstream protective layer or the unprotected bed further downstream can become damaged. Note that the existence of significant scour holes downstream a barrage causes undermining of the bed material below the barrage foundation. This might cause a collapse of the barrage.

The two types of methods that have been applied are:

1. Analytical (empirical) approaches have been used to calculate the expected scour depth for increased discharge conditions. Existing equations for predicting scour depths downstream barrages or low head structures are limited to laboratory studies using coarse sediments, i.e. Breusers and Raudkivi [1]. Therefore, a new analytical equation for predicting scour downstream low head structures has been developed by Hafez [4].
2. Scale model tests have been carried out for local scour prediction downstream of Rosetta barrage for high releases at HAD

ANALYTICAL APPROACH

Prediction of scour in case of higher releases from HAD have been made using the Hafez [4] equation developed for estimating equilibrium scour depth downstream of low head hydraulic structures. The equation is based on the same principles of the energy balance theory that was used for predicting bridge pier scour:

$$D_s^3 = \frac{6\eta^2 q^2}{g\left(S_G - 1\right)\left(1-\varepsilon\right)\left(\frac{1}{s_1}+\frac{1}{s_2}\right)\sin\phi_1}\left(1+\frac{D_s}{H_j}\right)$$

in which

D_s = equilibrium or maximum scour depth

H_j = the water depth of the incoming jet

q = the unit width discharge of the jet

S_2 = the upstream and downstream slopes of the scour hole respectively

ϕ_1 = the angle of the upstream slope of scour hole,

η = a momentum transfer coefficient,

In case of unavailability of data about q, the maximum jet velocity as an under flow could be calculated from the formula $V=\sqrt{(2gH)}$. For example, from a model study for the New Nag Hammadi barrage a jet velocity in the order of 9.45 m/s for flow under a sluiceway radial gate at normal conditions has been reported. This jet could be an underflow jet that in the absence of a weir downstream the barrage keeps its momentum till it meets the unprotected bed. The value of η is taken equal to unity for maximum scour depth. As the method is designed for Nile conditions, it performs better for the Nile barrages than other general empirical formulas for local scour.

In Table II an overview is given of observed scour (at current conditions) and predicted scour (at increase flow releases of HAD) at the main barrages that are investigated by HRI. The barrages built before HAD have about 100 gates (or about 50 gates in the delta branches) of about 5 to 8 m width. The New Esna barrage consists of a power house with 6 gates and a flood sluiceway with 11 gates, of 12 m width each. It can be seen that the predicted scour depths reach quite significant values when only a limited number of gates is operated. For Asyut, Rosetta and Damietta barrages the possibility of undesirable conditions during gate closure requires a rip-rap protection over the full width of the barrage.

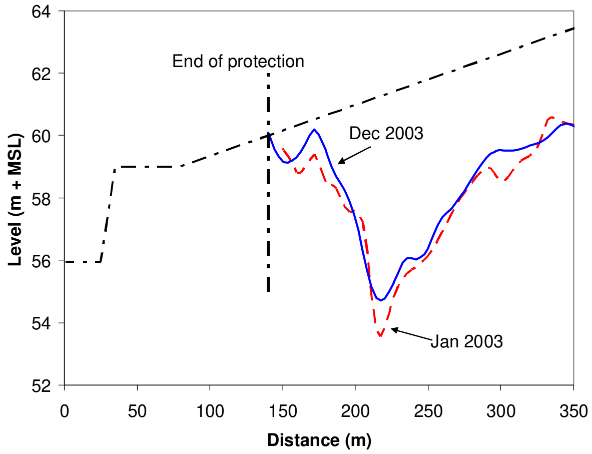

Figure 5 Scour Hole Downstream the New Esna Barrage at Turbine Gate No. 1

In Figure 5 the observed scour a New Esna barrage downstream of turbine gate 1 is plotted, with a scour depth up to 8 m. Its shape is typical for the scour holes at this barrage and the new Naga Hammadi barrage. The upstream slope of the scour hole S_1 = 0.11 and the downstream slope S_2 = 0.05. For predictions we used the jet depth H_j = 3 m, and at a flood discharge of 400 MCM/day the unit discharge q = 35.1 m^2/s from the sluiceway gates. For the sluiceway gates this results in a scour depth of 9 m (see Table II).

TABLE II.
LOCAL SCOUR AT BARRAGES, OBSERVED AND PREDICTED BY HRI

Name of structure	**Condition (flood = 400 MCM/d)**	**Observed (m)**	**Predicted (m)**
New Esna sluiceway	current	3 – 6.5	5.7
	flood		9
Nag Hammadi	current	< 10	8.7 -11
	fld, 100 gates		2.91
	fld, 50 gates		5.15
	fld, 20 gates		11.5
Asyut Barrage	current	< 7.5	8.4
	fld, 111 gates		3.1
	fld, 55 gates		5.6
	fld, 20 gates		13.5
Delta Barrage on Rosetta	current	4 – 4.7	4.75-5
	fld, 46 gates		4.3
	flood, 46 gates+d/sweir		3.8
Delta Barrage on Damietta	current	2 – 3.3	4
	fld, 34 gates		2.3
	flood, 34 gates+d/sweir		2.5
Zefta (Damietta)	current	3.5	4.2
	fld, 50 gates		2.4
	flood, 50 gates+d/sweir		2.4

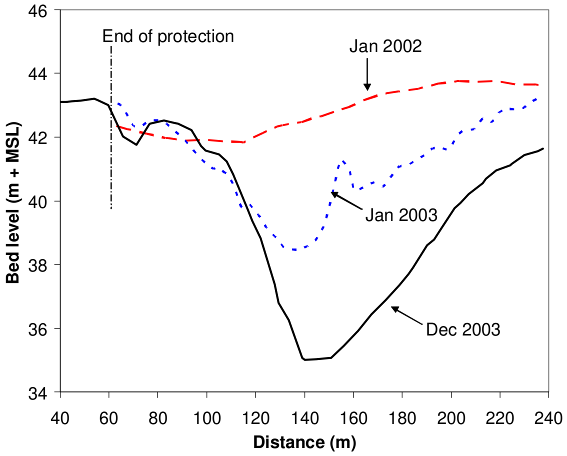

Figure 6 Scour Hole Downstream the Asyut Barrage at Vent No.58

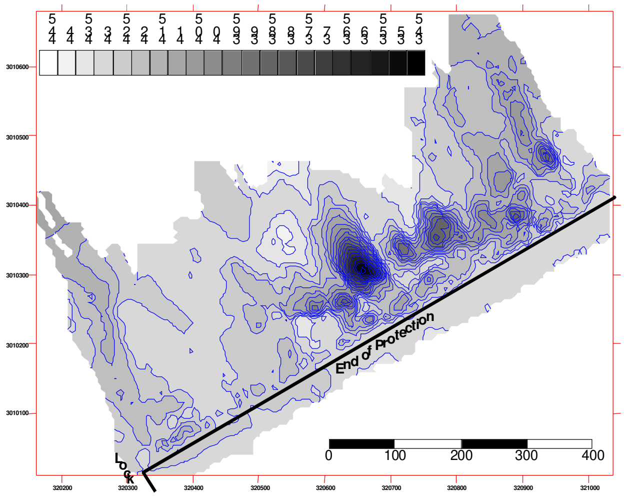

Figure 7 Bed Topography of the Scour Holes Downstream Asyut Barrage, December 2003

In Figure 6 and Figure 7 some observations of scour holes downstream of Asyut barrage (from HRI) are plotted. A particularly large scour hole has developed below vent No. 58. In Figure 6 it is shown that this scour hole developed in stages in the period between Dec 2002 and Dec 2003, up to a scour depth of 7.5 m. With the formula of Hafez [4] a scour depth of 8.4 m is predicted for this situation, which agrees reasonable with the data.

For Delta barrage at Rosetta branch (see Figure 9) it is shown in Table II that the predicted scour for floods is less than the current scour depth provided that all gates are open. For this prediction it is assumed that during a 400 MCM/day flood about 70% of the total discharge will pass through the Delta barrage at Rosetta branch (the rest will pass through Damietta branch). Distinction is made between the scour directly below the structure, and that below the downstream weir. The downstream weir is applied to reduce the jet-velocities (of about 9 m/s) with about 40%, and a scour depth below the weir of 3.8 m is predicted for flood conditions.

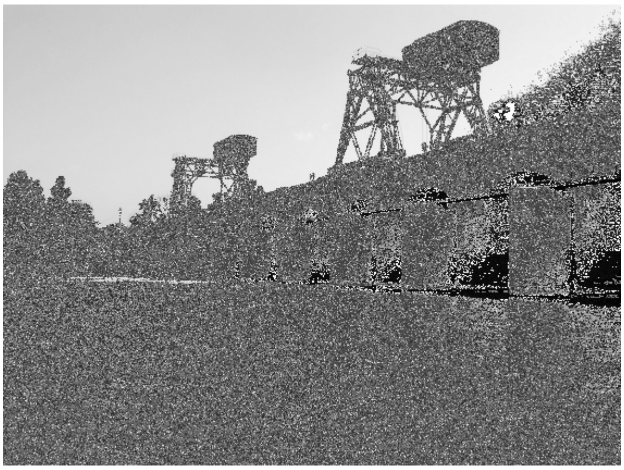

Figure 8 Delta barrage (d/s) in Rosetta branch

SCALE MODEL

The analytical model provides reasonable estimates of the maximum scour depth. However, more detailed information is required for design of the bed protection and scour-hole characteristics. Therefore movable-bed scale model tests have been carried out at HRI. Tests were run for a range of discharges between 150 to 400 MCM/day at the barrage (i.e. up to releases of 605 MCM/day at HAD). A geometrical scale of 1:32 was selected for best simulation of hydraulic phenomena with smallest possible scale effects. The model represents 100 m of the river bed upstream, 5 of the gates, the stilling basin, and 150 m of the downstream river bed (see Figure 9).

Figure 9 Scale model test for Rosetta Barrage: construction of the model at HRI

The experiments show that the maximum scour depth at 275 MCM/day (all 5 gates open) is 3.10 m, with scour length of 43 m. Compared to the analytical value for this condition, 4.3 m, this value is slightly lower. For a discharge of 400 MCM/day the maximum scour depth becomes 5 m if all 5 gates are opened, and 7 m if one of the gates is closed (see Figure 10, middle gate closed). The experiments confirm that as long as the flow is evenly distributed (all gates opened) the scour will not form a threat (it does not exceed the present scour depth).

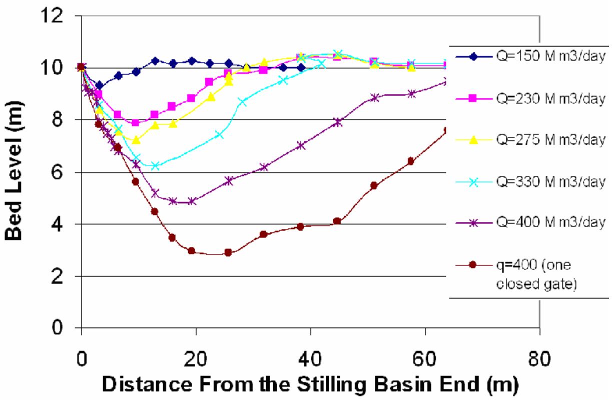

Figure 10 Bed levels downstream at section 9 (right side of flume)

To anticipate on an unequal opening of the gates, a rip-rap protection has been designed that will withstand these undesirable conditions. It requires a sand-base filling of the present scour hole, two filter layers with particle size 3 and 30 mm, and a rip-rap layer with thickness of 0.6 m over the full length of the scour hole.

V. BANK EROSION

The process of bank erosion in the lower Nile is related to both meandering and to general scour or river-bed-degradation. Currently bank erosion processes are limited to the absence of floods due to operation of HAD, degradation processes initiated by HAD have more or less diminished. Areas that used to be threatened by scour and bank erosion, such as islands and outer bends of meanders are now cultivated and developed, and have become much more vulnerable.

Figure 11 Bank erosion near Beni Suef (Nile main branch)

River banks in the lower Nile are cohesive and rather steep. Bank failure usually shows as sliding of bank section after undercutting. An example of failure that occurred during the flood release of 2001 is shown in Figure 11.

At most locations vulnerable for bank erosion the banks are already protected. Nevertheless, six locations have been identified which may suffer from bank instability during high floods. At these locations bank protection works have been designed.

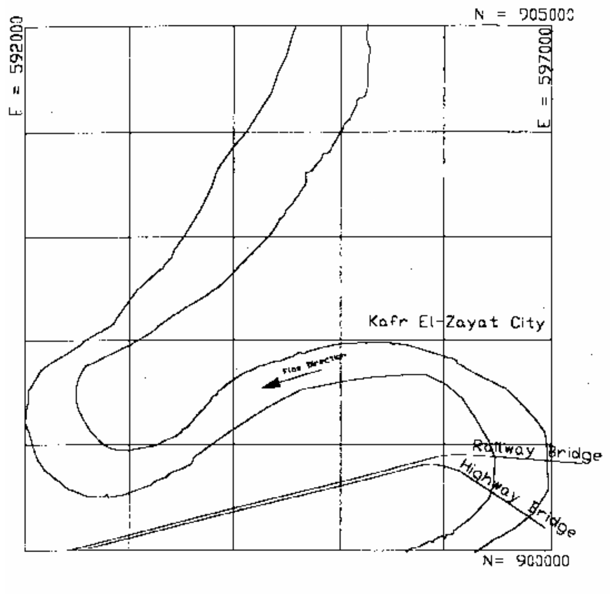

Figure 12 River bend at Kafr el-Zayat (Rosetta branch)

For the river bank at Kafr el-Zayat, located in a sharp bend at the Rosetta branch (see Figure 12) in the Nile delta, a detailed study has been carried out to improve the existing (inadequate) bank protection for resisting the flood releases from HAD. In Figure 13 is shown how currently the city is protected by rip-rap toe and a concrete slab.

Figure 13 Protected bank in river bend at Kafr-el-Zayat (Rosetta branch) just downstream of the railway bridge (right bank)

The detailed design for improvement of the bank protection is based on modelling study by HRI using a 2D hydraulic model. For different flood discharges the relevant flow conditions near the river bank have been determined.

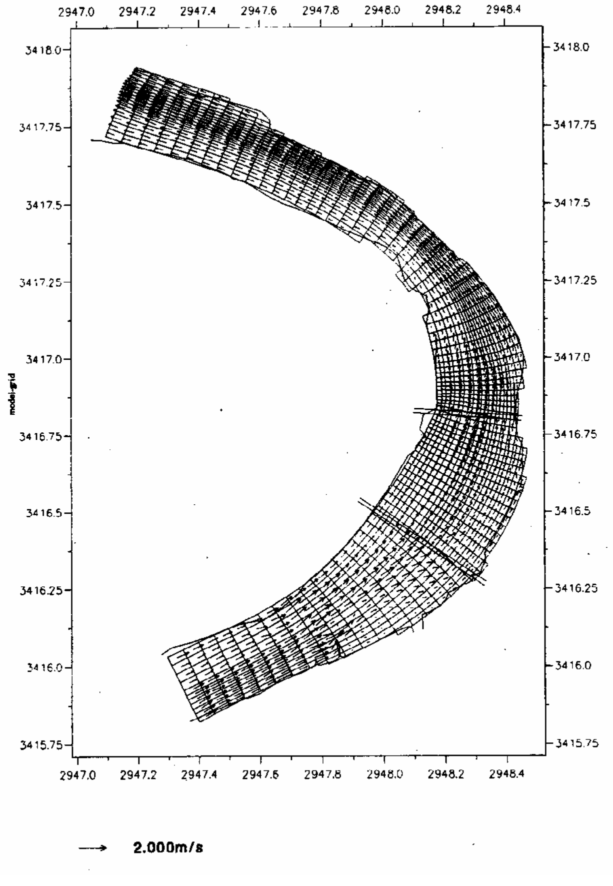

Figure 14 Velocity vectors in the modeled reach Kafr-el-Zayat

The hydraulic simulations were carried out using the Delft3D modelling system of WL | Delft Hydraulics [3].

In Figure 14 the velocity vectors are shown on the curvilinear grid following the alignment of the main river. The model has been calibrated on basis of field measurements in 1999 for two cross-sections. The model results show that the maximum velocity occurs in the cross-section at 850 m downstream of the railway bridge. The maximum velocity ranges from 0.9 m/s (Rosetta discharge 150 MCM/d, i.e. 240 MCM/d at HAD), 1.5 m/s (Rosetta discharge 275 MCM/d, i.e. 432 MCM/d at HAD), to 2 m/s (Rosetta discharge 440 MCM/d, i.e. 605 MCM/d at HAD). To protect the river bank against the resulting bend scour at Kafr El-Zayat several types of retaining walls have been proposed. They are founded well below the expected scour depth that is associated to the flow velocities computed for floods.

VI. DISCUSSION

The regulation of Nile discharges by HAD has removed the threat of flooding and scour. In the past decades the area around the river (flood plains) and within the river (islands) has gradually been developed and has become more vulnerable. Furthermore, the river has incised significantly at several reaches, such that river banks have become relatively high and steep with potential risk of failure. Although most of the structures (bridges and barrages) existed already before HAD, and therefore have strong protections, it was found that this does not mean that presently these can still withstand the flood discharges. It requires a careful operation of gates at barrages (e.g., following pre-HAD rules) and protection of river banks that have become critical with respect to stability. The problems and conditions in the lower Nile can be considered representative for many other reservoirs as well. The modifications in rivers downstream of high dams (both anthropogenic and natural) can become significant after some decades, resulting in an increased risk of damage by scour. The Nile example shows that protection against scour may be an important issue for the future reservoir management.

VII. CONCLUSIONS

Anticipating on climate change the operation of reservoirs may be modified in such a way that periodic flood discharges have to be released to the downstream reach. For the Nile this means an expected release of flood discharges for a period of several weeks through the lower reach. Damages in the downstream reach are to be expected as the (use of the) river-channel has changed significantly after floods have been diminished by the High Aswan Dam.

The most important damage caused by these manmade floods is expected to be caused by local scour. For the main Nile branches the most vulnerable locations have been determined, and the expected conditions have been predicted from analytical, numerical and laboratory scale modelling results. Particularly bank-erosion and bridge-pier scour processes have been estimated using mathematical modelling approaches designed for the Nile conditions. Whereas most bridge piers are already sufficiently protected, it has been concluded that only the river banks require an additional protection at several locations, and require inspection after each flood.

Furthermore laboratory experiments have been carried out to assess the scour downstream of Rosetta barrage which is governing the discharge distribution to the Nile delta. The mobile-bed model results appeared to agree with observations very well, and can be used for improvement of the theoretical models. It has been found that only by distributing the flood discharge over all the vents (instead of a few vents as is common practice) the scour depth will not exceed the present scour depth. Nevertheless it is necessary to protect three of the main barrages against local scour, as their present protection appears to be insufficient to withstand the high floods.

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