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Prediction of deposited sediment at the entrance of Toushka project

ABDEL AZIZ TAREK MOHAMED
Head of Hydrographic Survey and Mapping Unit, Nile Research Institute (NRI), National Water Research Center (NWRC), Qanatir, Egypt

Abstract
The south valley canal aims to create a new civilization and society where it is expected to serve water for the agriculture of about 540000 feddans. The entrance of this canal is located 10 km downstream Toushka spillway (250 km upstream Aswan High Dam-AHD). The most important component of Toushka project is the huge pump station. It consists of 21 pumps (18 are operational and 3 are stand by). They take water from AHD reservoir through a channel of about 4km length. It is of utmost importance to predict the amount and time needed for sediment to reach this channel. One-dimensional model for sediment transport and consolidation in Aswan High Dam Reservoir-AHDR (Abdel-Aziz T.M. 1991) is used for this purpose. The model is based on the principle equations of water volume conservation, water momentum conservation and a general sediment transport equation, based on an improved rating curve for Dongola station at the inlet and a modified Shield's equation at the reservoir. Also, an improved consolidation model independent of the sedimentation time was used, where the average bed density was calculated as a mass balance of the existing consolidating sediments influenced by deposition or erosion. The model shows that the average thickness of deposited sediment at Toushka cross section (256 km upstream AHD) is 13 cm in year 2000 from the beginning of reservoir operation (in May 1964). This is very close to the actual measurements. Consequently, more runs were done for the model to predict the average thickness of deposition in 2010. It is expected to reach about 19 cm, which indicates that the rate of deposition is about 3 cm every 5 years at the location of the pump station.

INTRODUCTION

The high density of population in the River Nile valley and delta and the spread of shanties that could threaten social peace and security made of expansion and redeployment of Egyptian communities, a necessity and not an option. The triggering of the first signal announcing the implementation of "South Egypt Development Project" Toushka is a true expression of the dream that the Egyptians have entrained, since time immemorial, and longed for its realization. Toushka project is a strategic vision that will drive Egypt to the horizons of the 21st century, embracing a number of development fields covering activities in the field of agriculture, industry, transport, communication and roads, as well as social aspects and services.

BACKGROUND AND AIM OF THE WORK

For the agricultural water requirements, it has been estimated that the average evapotranspiration for the project area is 4.97 mm daily. Accordingly the annual water required for each feddan within the area has been calculated to be within the range of 8000 m^3 including leaching requirement which is estimated at 20 % of the total water requirement. This amount can definitely be much less in case of using modern irrigation technology. The total amount of water required will be within Egypt's share of Nile water, defined by the 1959 Nile Water Agreement. The project starts with a giant major pumping station to be set up on the left bank of Aswan High Dam Reservoir 10 km north of Khor Toushka to be constructed in 4 years starting 1st January 1998. The station has been designed to have a maximum static lifting of about 52.5 m to guarantee its operation when the water level in Aswan High Dam reservoir reaches its lowest level of storage (147 m above Mean Sea level). 21 pumps, each with a discharge capacity of 16.7 m^3/sec, will be housed inside the pumping station, 18 pumps of which will be on duty while the rest 3 will act as standby units. The most important component in the project is the pump station, the designed discharge of pumping station was estimated to be about 300 m^3/sec (25 million m^3/day) subject to rise if necessary while withdrawal would be from the intake through an open basin and discharge through a pipeline. So it is very important to keep this intake free of sediment. Therefore the prediction of sediment transport and its rate towards the intake of the pump station is necessary to find out the suitable way and time to deal with the sediment in the open basin.

TOPOGRAPHY OF ASWAN HIGH DAM RESERVOIR (AHDR)

Aswan High Dam is a rockfill dam, 111 m in height and 3600 m in length closing the Nile at a distance 6.5 km south of Aswan. The length of AHDR is about 500 km at its maximum storage level, which is 182 m, with an average width of about 12-km and a surface area of 6540 km^2. The water level upstream the dam defines the surface area and the volume of water in the reservoir. These relations may be written as: -

$$A = 6.493*10^{-11} \quad W^{6.19} \qquad (1)$$

$$V = 8.578*10^{-17} \quad W^{8.098} \qquad (2)$$

Where A: surface area in km^2, W: water level just upstream AHD in m, and V: water content in 10^9 m^3.

DIMENSIONS OF SOUTH VALLEY CANAL (TOUSHKA)

The main canal, with 70 km length has been designed to convey water to several branches as follows: -The first branch canal is 42 km in length serving an area of 120000 feddans. The second branch canal is 35 km in length serving an area of 120000 feddans. The third branch canal is 20 km in length serving an area of 100000 feddans. The fourth branch canal is 60 km in length serving an area of 200000 feddans. The cross section of the main canal was designed to be lined to prevent any water leakage with a bed width of 30 meters and water depth of 6 meters, in addition to one meter free board, with an upper width of 54 meters with platforms on the two sides 8 meters wide, and 20 meter-wide banks.

THE EQUATIONS OF SEDIMENT TRANSPORT MODEL IN AHDR
Water Volume Conservation

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \tag{3}$$

Where A: cross sectional area =h .b, h: water depth,
b: width of cross section at water surface, q: lateral in or out flow,
Q: water discharge x: longitudinal section, t: time

The following assumptions have been applied in AHDR:

For more or less prismatic channels the change of the cross sectional area with respect to distance almost equals zero.

For wide cross sections, the hydraulic radius equals the depth of flow.

Since the flow is gradually varied, i.e. The Froude Number values are moderate, We can approximate the flow from Non-steady flow to Pseudo flow.

There is no lateral inflow or outflow in the reach between Dongola station (750 km up-stream AHD) and the inlet of AHDR (500 km upstream AHD), therefore we will assume q = 0

$$b\frac{\partial h}{\partial t} + h\frac{\partial b}{\partial t} = -\frac{\partial Q}{\partial x} \tag{4}$$

$$(b + h\frac{\partial b}{\partial h})\frac{\partial h}{\partial t} = -\frac{\partial Q}{\partial x} \tag{5}$$

$h = (Z_w - Z_b)$, Z_w: water level, Z_b: bed level

We will assume

$$\frac{\partial Z_b}{\partial t} \prec\prec \frac{\partial Z_w}{\partial t} \tag{6}$$

then

$$\frac{\partial h}{\partial t} = \frac{\partial Z_w}{\partial t} \tag{7}$$

Hence

$$(b + h\frac{\partial b}{\partial h})\frac{\partial Z_w}{\partial t} = -\frac{\partial Q}{\partial x} \tag{8}$$

Water Momentum Conservation

$$Q = \left(-\frac{\partial Z_w}{\partial x}\right) AC\sqrt{h \left| \frac{\partial Z_w}{\partial x} \right|} \tag{9}$$

Where C: Chezy coefficient

Sediment Transport Equations

For quasi-steady state, one dimensional flow:

$$B(1 - p)\,\rho_s \frac{\partial Z_b}{\partial t} + \frac{\partial Q_s}{\partial x} = 0 \tag{10}$$

B: width of cross section at the bottom level
Z_b: bed level elevation
P : is the sediment porosity
ρ_s: is the density of sediment particle (2650 Kg/m3 in case of AHDR)
Q_s: is the sediment load

Let ρ_d = (1-p) ρ_s
= sediment dry density which is time dependent because of consolidation. Hence,

$$B\,\rho_d \frac{\partial Z_b}{\partial t} = -\frac{\partial Q_s}{\partial x} \tag{11}$$

In order to calculate Qs, we will use an empirical relation of the form:

Qs = Qb(U)*B where U = Q/A the average flow velocity.

Sediment load at the whole reservoir at the time step t, is given by the reservoir rating curve.

Boundary conditions are only needed at the inlet where the Dongola rating curve gives the sediment load.

AHDR rating curve

The available data sets for the period from 1980 to 1988 were used to calculate the sediment load per unit width Q_b as a function of velocity. Since the sediment load can be measured accurately, it was more logical to do the regression of the velocity as a function of the sediment load; and the following equation was found:

$$Q_b = 1.2 \times U \tag{12}$$

where U: is the velocity of the flow in (m/s)
Q_b: is the sediment load per unit width (Kg/m.s)

In the measurements of the defined period, the higher velocities were missing, therefore it was necessary to modify this equation to have a good representation either to low or high velocities. Therefore theoretical models have been tested using the available data of the sedimentation zone, which starts from the inlet section at Km 500 upstream AHD to Km 325. The tested models are:

(1) Bagnold's model.
(2) Meyer-peter and Muller Model.
(3) Shields model.

In view of the results, it is noted that Bagnold's model could be applied only in the inlet zone and the estimated load per unit width is close to the measured one when the velocity is high.

Meyer-peter and Muller model does not give reliable results. Shields gives good results almost along the whole reservoir especially in case of high discharge. Based on these results, it was proposed to use a simplified shields equation where all the terms have been expressed as a function of the velocity only.

Shields equation is stated as

$$Q_b = 10\, q_0\, i \frac{\tau_0 - \tau_c}{\left(\frac{\rho_s}{\rho_f} - 1\right)^2 d_{50}} \tag{13}$$

Where Q_b: is the sediment load per unit width in (kg/m.s)
q_0: is the water discharge per unit width in (m^3/m.s)
i: is the slope of the energy gradient line
d_{50}: is the mean diameter of bed material in (m)
τ_0: is the average shear stress in (N/m^2)
τ_c: is the critical shear stress in (N/m^2)
ρ_f : is the density of fluid in (Kg/m^3)
ρ_s: is the density of sediment in (Kg/m^3)

$$q_0 = \frac{Q}{A} = \frac{AU}{B} = h.U \tag{14}$$

$$U = C\sqrt{h * i} \tag{15}$$

$$i = \frac{U^2}{C^2 h} \tag{16}$$

$$\tau_0 = \mathrm{g}\left(\frac{U}{C}\right)^2 \tag{17}$$

where h: hydraulic radius in (m)
C: Chezy coeff. = 50 $m^{0.5}$/s in case of AHDR (Abdel-Aziz, T. M. 1991)
g: is the gravity acceleration in (m/s^2)

From the actual measurements in the Aswan High Dam reservoir during the period 1964 - 1988, it was found that the mean diameter of bed material= 0.14 m, and the average critical shear stress= 0.02 Newton/m^2 (Abdel-Aziz, T. M. 1991).
Then

$$Q_b = 10\frac{U^3}{g(50)^2}\left(\frac{1000(9.81)\frac{U^2}{(50)^2}-0.02g}{2.7225\,d_{50}}\right) \tag{18}$$

$$Q_b = 4.16\,U^5 - 0.21\,U^3 \tag{19}$$

A comparison between the sediment load per unit width Q_b measurements in the same period and the calculated values using Shields equation has been made. It is noted that Shields curve is accurate only for the high velocities, Therefore the following equation was proposed:

$$Q_b = 1.2\,U + 4.16\,U^5 - 0.21\,U^3 \tag{20}$$

This model rating curve fits the measurements and it is tangent to Shields curve in the high measurements, therefore the model rating curve is more appropriate.

Dongola sediment rating curve

We assume a relation of the following form

$$Q_s = a.Q + b.(Q)^c \quad \text{or} \quad S.Q = a.Q + b.(Q)^c \tag{21}$$

Where S: is the average sediment concentration in (Kg/m^3)
Q_s: is the sediment load in (Kg/s)
Q: is the discharge in (m^3/s)
a,b and c are constants.

Therefore $S = a + b.(Q)^{c-1}$

$$\frac{S-a}{b} = Q^{c-1} \tag{22}$$

or

$$Q = \left(\frac{S-a}{b}\right)^{\frac{1}{c-1}} \tag{23}$$

S can be measured accurately but large errors are present for Q, hence a,b and c should be determined such that the sum of squared differences between measured and calculated Q values is minimum. This can be done with non-linear optimization programs. Based on the least square difference, the three coefficients a,b and c were calculated and the mathematical equation of Dongola (inlet station) rating curve was found:

$$Q_s = 0.1\,Q + 8.9\text{x}10^{-11}\,Q^{3.744} \tag{24}$$

In the computer model for sediment transport and consolidation, the average bed density is calculated as a mass balance of the existing bed sediments influenced by deposition or erosion.

$$d[\rho (Z_b - Z_{b0})]/dt = r \quad (25)$$

Where r: is the deposition rate or the erosion rate in case of negative value.

Or

$$(Z_b - Z_{b0})d\rho/dt + \rho [d(Z_b - Z_{b0})]/dt = r \quad (26)$$

The second term on the left side is the change of the bed level when ρ remains constant, hence this is the change only due to deposition or erosion.

In case of deposition

$\rho = \rho_{min}$ then

$$(Z_b - Z_{b0})d\rho/dt + \rho_{min} d(Z_b - Z_{b0})]/dt = r \quad (27)$$

$(Z_b - Z_{b0})d\rho/dt = 0$ because ρ is constant

$$0 + \rho_{min} [d(Z_b - Z_{b0})]/dt = r \quad (28)$$

then

$$[d(Z_b - Z_{b0})]/dt = r / \rho_{min} \quad (29)$$

$$(Z_b - Z_{b0})d\rho/dt + \rho (r / \rho_{min}) = r \quad (30)$$

$$(Z_b - Z_{b0})d\rho/dt = r - r (\rho / \rho_{min}) = r [1 - \rho / \rho_{min}] = r (\rho_{min} - \rho) / \rho_{min} \quad (31)$$

$$d\rho/dt = r (\rho_{min} - \rho) / \rho_{min} (Z_b - Z_{b0}) \quad (32)$$

Then in the computer model, the density at the time step t + dt can be calculated as follows:

$$\rho^{t + dt} = \rho^{t} + r (\rho_{min} - \rho^{t}) / \rho_{min} (Z_b - Z_{b0}) \quad (33)$$

In case of erosion

$$d(Z_b - Z_{b0})]/dt = r / \rho \quad (34)$$

$$(Z_b - Z_{b0})d\rho/dt + \rho (r / \rho) = r \quad (35)$$

$$(Z_b - Z_{b0})d\rho/dt = 0 \tag{36}$$

$$\text{then} \quad d\rho/dt = 0 \tag{37}$$

The deposited sediment volume in AHDR using the measured data from 1964 to 1998 is estimated. It was found that the minimum density of the deposited sediment in AHDR is 1200 kg/m^3 and the maximum density is 1400 kg/m^3.

Table 1: The estimated bed level for the period (2003-2010) and the original one (May 1964)

x-sec	x-u/s	Zb	Zb	Zb	Zb	Zb	Zb	Zb	Zb	Zb
No.	AHD	6419	2003	2004	2005	2006	2007	2008	2009	2010
1	487.5	139.80	170.93	170.81	168.64	170.51	171.13	169.36	166.27	164.18
2	466.0	132.04	172.49	171.72	170.45	171.25	171.38	169.75	166.63	164.58
3	448.0	136.12	170.76	169.55	169.37	169.12	168.67	167.77	165.15	163.43
4	431.0	137.62	174.09	173.23	172.13	171.62	171.62	169.97	167.54	165.94
5	415.5	126.10	173.34	172.53	171.72	170.51	169.75	167.93	165.93	164.68
6	403.5	124.30	172.32	171.47	170.89	169.20	167.47	165.76	163.82	162.66
7	394.0	116.32	172.96	172.14	171.32	169.58	167.97	166.02	164.68	163.76
8	378.0	110.17	171.57	170.65	169.82	167.95	165.44	162.55	162.15	161.57
9	372.0	109.92	171.88	170.92	169.78	168.16	166.44	163.33	163.18	162.71
10	368.0	110.07	172.39	171.37	169.81	168.54	167.07	163.74	163.75	163.37
11	364.0	122.29	172.98	171.82	169.65	169.34	167.79	164.12	164.27	163.97
12	357.0	113.43	172.55	171.24	168.52	167.16	163.09	163.26	163.54	163.39
13	352.0	105.16	160.22	164.84	168.32	164.09	159.80	163.11	163.31	163.24
14	347.0	111.99	132.02	132.23	136.05	148.04	159.32	162.21	162.48	162.43
15	331.1	110.01	126.55	126.56	126.57	126.73	133.62	139.52	144.93	148.97
16	325.0	110.00	121.73	121.73	121.73	121.73	121.75	121.79	121.87	121.98
17	307.0	108.01	112.12	112.14	112.16	112.20	112.28	112.34	112.39	112.44
18	282.0	103.02	105.69	105.72	105.74	105.78	105.85	105.92	105.97	106.01
19	256.0	105.00	105.14	105.14	105.14	105.15	105.16	105.17	105.18	105.19

APPLICATION OF THE MODEL

The model solves the partial differential equations governing the water flow, sediment transport and consolidation under Pseudo state conditions; from equation 1 to equation 6. The distance from the inlet of AHDR (500 km upstream AHD) to the location of pump station at Toushka project (250 km upstream AHD) was covered by 20 cross sections. The main purpose of these cross sections is to establish fixed locations where direct measurements of deposited sediment can be done periodically as part of the hydrographic surveys. The results for the bed shape from year 2000 to year 2010 have been indicated in table 1. These results have been compared to the original bed shape of AHDR in May 1964. It is noted that there are movable waves of erosion and deposition along the distance from cross section 1 at km 487.5 upstream AHD to cross section 18 only at km 282 upstream AHD. The bed level at Toushka cross section at km 256 upstream AHD does not change from year 1965 to year 2000. To investigate the location of pump station deeply, the model has been run till year 2010. Out of the results, the bed level at Toushka cross section was 105.13 m in 1965 and would continue the same until year 2002. It will start to change by year 2003 with a very low rate. By year 2010, the bed level was estimated to be 105.19 m. Accordingly, the change rate is about 3cm every 5 years. To have a little deposition at the location of the pump station, about 0.25m for example, It needs about 40 years.

DISCUSSION OF RESULTS

A comparison between measured and calculated bed level for years 1994 and 1996 are indicated in figure 1 and figure 2. It is observed that the estimated bed level is somewhat higher than the measured along the inlet zone (from km 500 to km 375 upstream AHD). In the model however, the cross sections are considered to be rectangular with the same width at the water level and an average depth. It means that the calculated bed level is an average while the measured is the lowest. In the locations near the pump station, the difference between the measured and the model bed level is small. Generally, the comparison between the measured and the estimated bed levels indicates good results.

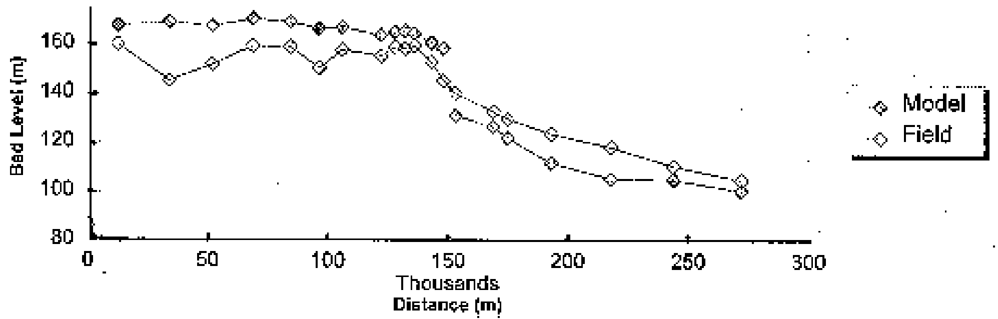

Figure 1. Comparison between measured and calculated bed level during year 1994.

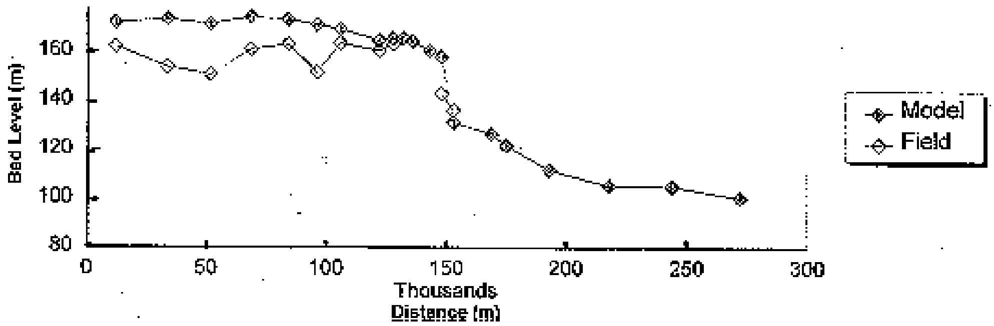

Figure 2. Comparison between measured and calculated bed level during year 1996.

CONCLUSION

Based on the results of the one dimensional model for sediment transport and consolidation in AHDR in the region between inlet cross section and location of pump station, we conclude that:-

The estimated bed shape is close to the measured one along the whole zone especially the region near the pump station.
The waves of erosion and deposition take place from the inlet until Abou Simple cross section only (282 km upstream AHD). Accordingly, there are about 30 km upstream the location of the pump station which do not have any change in the bed level since the beginning of AHDR (in May 1964).

The time needed for sediment to reach the pump station in a considerable value is estimated about 40 years.

The rate of deposition at the location of Toushka project is about 3 cm every 5 years.

The location of Toushka project (pump station and open basin intake) is very suitable from deposition point of view where it is expected to stay stable for about 40 years at least. Additionally, when it starts suffering from deposition, the rate will be very small.

RECOMMENDATIONS

Application of two dimensional model in the whole sedimentation zone will be more representative than one dimensional model, since it will consider the effect of bed form in the transverse direction.

The field measurements should be carried out two or three times per year instead of one, especially around the location of pump station.

Production of contour maps for the bed levels around Toushka project location will help to find out any change around the pump station very fast.

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