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Towards better Management of Sediment and Water in Gezira Irrigation System, Sudan

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Abstract: The one dimensional numerical model Fine Sediment Transport (FSEDT) was developed to simulate the fine sediment transport in irrigation canals of the Gezira Scheme in Sudan. The model was used to understand the sedimentation processes in Gezira canals, as well as for possible wider application. The approach applied to estimate the transport and deposition rates of fine sediment suspensions, for sediments in the cohesive size range has been presented. The model was calibrated and validated using field measurement data at selected canals in the Gezira Scheme during 2011 and 2012 flood seasons. The simulated bed profile of the Zananda Major Canal shows good agreement with the bathymetric survey. The hydro-dynamic part of the model was checked by comparing the water surface profile of the model with that obtained by the DUFLOW model. The results of the two models show good agreement. The analysis demonstrates that the model is a useful tool that can be applied to study the mechanism of sediment transport under different operation and maintenance scenarios not only in Gezira Scheme but also in similar cases.

Keywords: *Irrigation; cohesive sediment; model; deposition and erosion*

1. INTRODUCTION

The dynamics of cohesive sediment transport are mainly treated empirically since they are affected by numerous parameters that cannot be determined [1]. Moreover, the combination of hydrodynamic, cohesive sediment properties and biological processes make the prediction of cohesive sediment dynamics difficult. The use of modelling tools improves the understanding of fine sediment dynamics. Therefore, a model to simulate the suspended sediment transport cannot be developed without deep understanding to the properties of the sediment under the study. This understanding is most expediently developed through the field data analysis and formulation of a conceptual model.

This study has been carried out in the Gezira Scheme in Sudan. The scheme, which is one of the largest irrigation schemes in the world under a single management, is located in the arid and semi-arid region. The scheme is chosen as a case study since it can act as a model for similar irrigation schemes. The scheme has a total area of 880,000 ha and uses 35% of Sudan's current allocation of Nile waters. This represents 6-7 billion m^3 per year. The scheme is irrigated from the Blue Nile River, which is characterized by its high load of fine sediment. The scheme is facing severe sediment accumulation in its irrigation canals, which represents a challenge to those responsible for the operation and maintenance of the canals. Each year large investments are required to maintain and to upgrade the canal system to keep it in an acceptable condition.

Zananda Major Canal was analysed under the study. Figure 1 shows the study area. It is the first canal that takes water from Gezira Main Canal. The characteristics of the canal are illustrated in Table I. There are two cross regulator type movable weirs at respectively 9.1 and 12.5 km from the off-take of the major canal with a crest width of 2 and 1.3 m. The cropping patterns in Gezira Scheme are; cotton, groundnut, sorghum, vegetables (garden) and wheat (winter crop). The operation of the scheme is based on on-demand irrigation and control by manual upstream control structures.

The aim of this paper is to apply a newly developed numerical model to simulate cohesive sediment transport in irrigation canals based on different operation scenarios and to come up with a strategy in order to reduce the sediment deposition in irrigation canals. First, the paper gives a brief description of the developed model to simulate the suspended sediment transport in irrigation canals. Then, it gives a summary of fieldwork and data analysis. This is followed by a section on results and discussion, which presents the different operation scenarios and their effect on sedimentation and finally the conclusions.

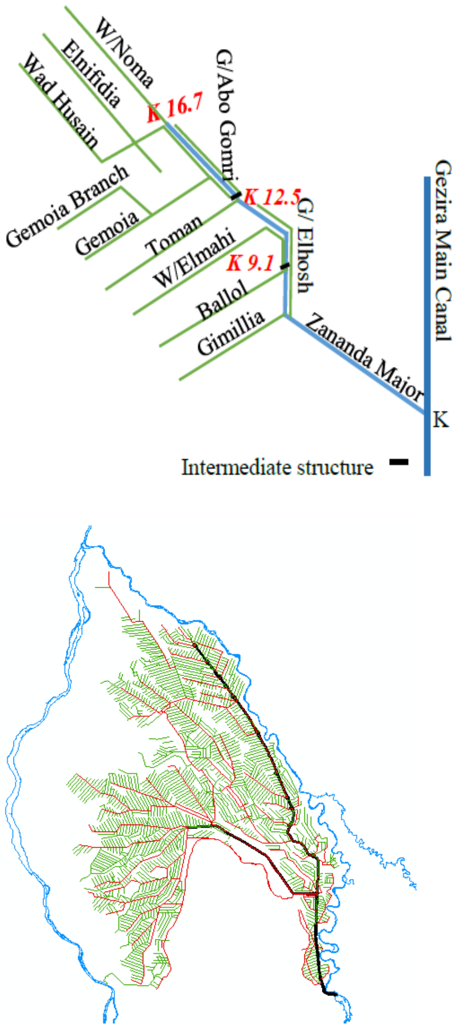

Fig.1: StudyareainGeziraScheme

2. MATERIAL AND METHODS

2.1 *Model Development*

The one dimensional model, Fine SEDiment Transport (FSEDT) was developed based on the water mass conservation equation, gradual varied flow equation, advection diffusion equation and sediment mass balance equation. The model has been used as a tool to study the mechanism of water and sediment flow under different operation and maintenance scenarios. The flow in irrigation canals is assumed to be steady non-uniform flow (gradually varied flow) during the time step. The supply is given as time series and the model computes the discharge at each point by applying the continuity equation. The water surface profile is predicted by using the predictor corrector method to solve the gradually varied flow equation. The model uses an uncoupled solution. The output of the hydrodynamic computation is input of the sediment computation. The model can compute the normal depth, critical depth, water depth and shear stress by assuming a logarithmic velocity distribution as a result of turbidity. The governing water surface equations [2] are as follows:

$$\frac{dy}{dx} = \frac{S_0 - S_f}{1 - Fr^2} \quad (1)$$

wheredy/dxiswaterprofileslope, S_f isfrictionslope, S_0 isbedslopeand*Fr*isFroudenumber. The computationoftheflowprofilestartsfromtheknownwaterdepth downstreamy(xn,t)for eachreach.Thecomputationstartsreachbyreachfromdownstreamtowardsupstream. Accuracyoftheprediction of thewater depth applied in the model is 0.005 m.

The suspended sediment transport computation is based on numerically solving the advection diffusion equation [3]. This equation was solved using the finite difference method

$$\frac{\partial C}{\partial t} + v\frac{\partial C}{\partial x} = \frac{1}{A}\frac{\partial}{\partial x}\left(AK_s\frac{\partial C}{\partial x}\right) + S \quad (2)$$

where*C* is concentration (kg/m^3), A is wetted cross section area (m^2), $K_s$is longitudinal diffusion coefficient (m^2/s) and *v* is flow velocity (m/s). The source/sink term (*S*) represents the water-bed exchange rate and takes into account the erosion and deposition of sediment per unit length. The computation relies on the [4] and [5] equations fordeposition (*D*) and erosion (*E*) rates respectively:

$$D = w_s C_b \left(1 - \frac{\tau}{\tau_d}\right) \quad (3)$$

$$E = M\left(\frac{\tau}{\tau_c} - 1\right) \quad (4)$$

where τ is bed shear stress (N/m2), τ_c is critical shear stress for erosion (N/m^2), τ_d is critical shear stress for deposition (N/m^2), *C* is the concentration near the bed (kg/m^3), w_s is settling velocity (m/s), *M* is re-adaptability coefficient (kg/m^2/s), *D* is deposition rate (kg/m^2/s), *E* is erosion flux (kg/m^2/s).

The approach of the critical shear stress of deposition not existing is followed according to [6][7] and [8].The sediment mass balance equation was solved numerically by using the finite difference method to obtain the change in bed profile:

$$\frac{\partial z}{\partial t} + \frac{1}{b\rho_s}\frac{\partial Q_s}{\partial x} = 0 \quad (5)$$

Where Q_s is sediment discharge (kg/s), *b* is bed width (m), ρ_s is sediment density (kg/m3), ∂z is bottom level above datum (m), ∂x is length coordinates in x direction (m).

The model can predict the sediment concentration hydrograph at any point and can present the result either in time series or in a graph. The model has the capability to estimate the change in the bed level with time. It is also possible to predict the sediment load, sediment concentration, water level and deposition along the canal at any time during the simulation period. The model has the capability to quantify the total volume of the sediment deposition per reach.

Table 1: Zananda Major Canal

Canalcharacteristics	Values
Positionofoff-takealongmaincanal(km)	57
Areaofcommand(ha)	8,520
Effectivelength(km)	17
Numberofreaches	3
Minorscanal supplied	9
Designdischarge(m^3/s)	3.52

3 DATA COLLECTION AND FIELD MEASUREMENT

Intensive data collection and field measurements were conducted between June and October in 2011 and 2012. Sediment sampling and water level measurements were done on daily basis at selected locations as shown in Figure 2. Cross-sectional surveys were performed at the beginning and end of the flood season (on June and October) to get the canal profiles and to address the distribution of sediment along the canal under study. The head regulator and outlets were calibrated by using the measured stage-discharge relationships. The relation of the head difference between the upstream and downstream water depth, gate openings and discharge in case of sluice gates was determined. Moreover, the operation schedule, cropped area and sawing dates were also recorded.

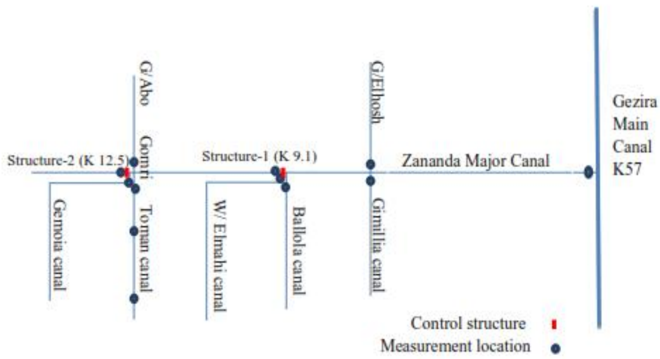

Fig. 2: Scheme of Zananda Major Canal and measurement locations

Based on the analysis of the field data it was found that although the cropped area at Zananda Major Canal was 3640 ha and 4680 ha in 2011 and 2012 respectively, more water was released in 2011 between mid-July and 10th of August. This period coincides with the period of high sediment concentration in the Blue Nile River. In 2011 the rainfall was concentrated in a short period, and an oversupply of the canal under study, especially between the second decade of July (July-II) and the first decade of August (August-I), has been detected. That resulted in a high sediment load entering the scheme. Figure 3 presents the crop water requirement, actual water delivered and the sediment load in 2011.

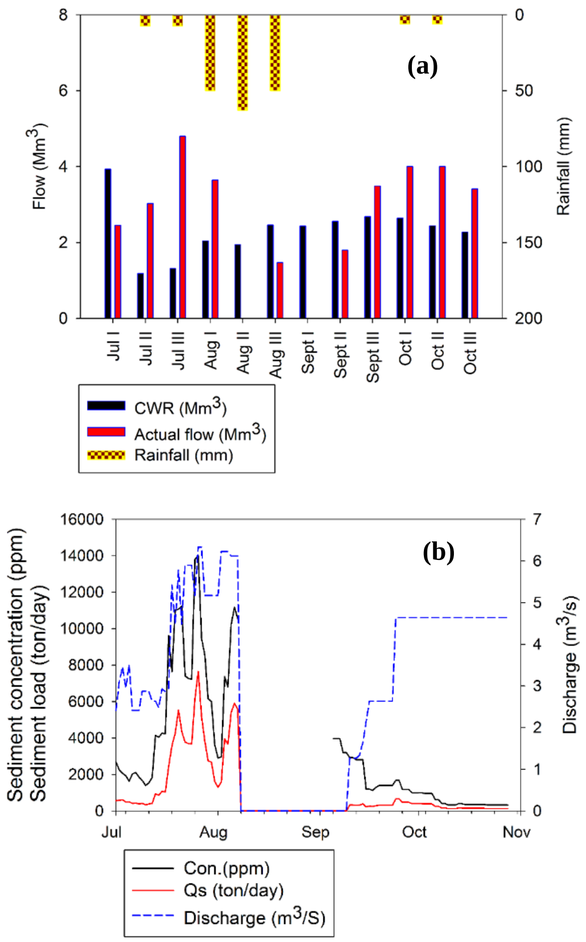

Fig. 3: Sediment concentration and flow discharge at the offtake of Zananda Major Canal in 201. a) Crop water requirement and actual release, b)Water released, concentration and sediment load at offtake

4 MODEL SETUP

The model was setup with the bed profile of the canal according to the bathymetric survey (cross sections every 200 m). The abscissa of each reach, the minor canal locations as in figure 2, and the width and side slope for each reach are defined in the model. The flow discharge and sediment concentration are set in time series at the upstream boundary condition. The outflow discharges along the canal during the simulation period are set in time series. The type of structures and their properties such as the discharge coefficient, width of weirs and exponential values are input to the model. The

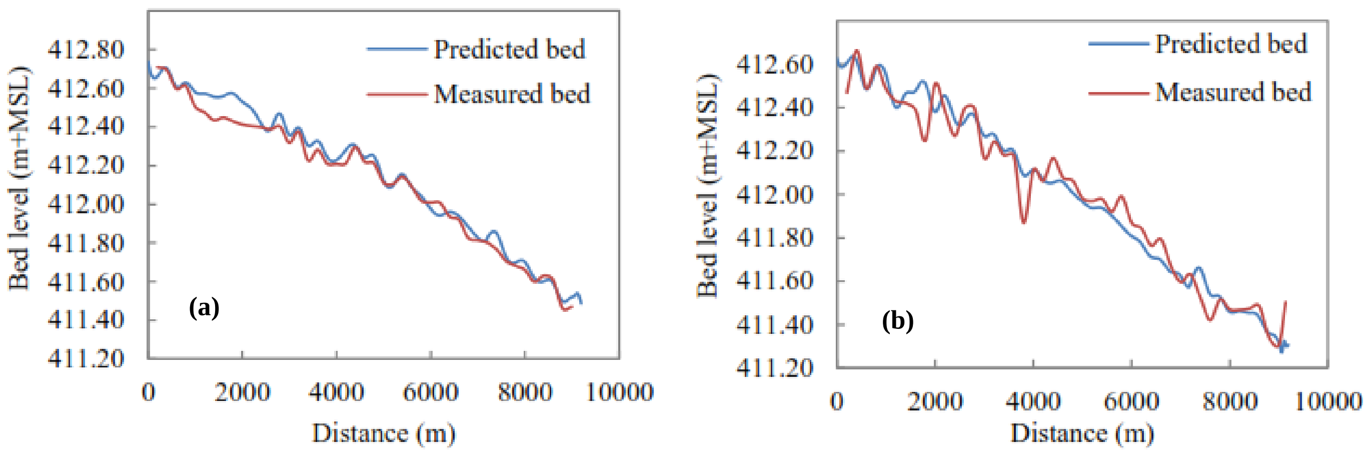

Fig. 4: Model calibration and validation. a) Modelcalibrationforthe2012floodseason, b) Modelvalidationforthe2011floodseason

sediment and flow properties such as particle density: 2740 kg/m^3, sediment density: 1200 kg/m^3, water density: 1000 kg/m^3, kinematic viscosity: 10-6 m^2/s are defined to the model.

The model was calibrated and validated by using the data collected for the first reach in 2012 for the calibration and in 2011 for validation. The predicted bed profiles are in good agreement with the field observations as shown in the Figure 4.The results of hydrodynamic computation (water surface profile) were compared with the results of the DUFLOW model. DUFLOW is a micro-computer program for simulating one-dimensional steady/unsteady flow in open canals. The model setup was based on the geometric data of the first reach of Zanada canal. The hydrodynamic part of the model was functioning adequately since the difference between the predicted water surface profiles by the two models was reasonable.

5. RESULTS AND DISCUSSION

5.1 *Operation Based On Different Scenarios*

The model has been applied to study the behaviour of the sediment at the first and second reaches of the canal under study. Two options of operation were tested and compared with actual situation in 2011. The model evaluated the indent system that has been applied in the Gezira Scheme for many years regarding to sediment deposition. A proposed scenario based on crop water requirement was also tested. Another scenario called "future scenario" was checked when the sediment concentration in the Blue Nile reduce by 50% as a result of soil conservation or construction of a new dams upstream

5.2. *Actual Situation in 2011*

Sediment concentration and flow discharge have been defined in the model in time series as upstream boundary condition. The crest levels of the cross structures were assumed constant at their lowest position during the simulation period according to the field observations. They were set at 411.10 m and 410.35 m for Structure-1 and Structure-2 respectively. The re- adaptability coefficient was taken at 0.0016 $kg/m^2/s$ and the critical shear stress for erosion was set at 0.1 N/m^2(calibrated parameters). Then, the sedimentation was simulated and a total deposition of 14,080 m^3 was predicted by the model for the first and second reaches.

5.3. *Scenario 1. Operation based on the indent system (authorized operation)*

The indent system has been applied in the Gezira Scheme based on the water duty and irrigated area. The aim of this scenario is to address how the sediment would behave if the canal would be operated based on the indent. The water duty is a procedure for water allocation. It is the number of hectares (feddan) of land irrigated per cubic meter per day of water in a crop season. It gives an approximate estimation of the water requirement over a gross period like a season. In the Gezira Scheme, the empirical method to estimate the requirements of all crops is 71.4 m^3/ha/day (30 m^3/feddan/day) inclusive of field losses at the head of the Abu Ishreencanals[9]. The delivered discharge to the major and minor canals is based on the duty and actual irrigated area in 2011. The sawing dates for sorghum were between 1st and10th June, groundnut between 20th and30th July and cotton between 1st and 10th of August. Therefore, the indent during July was based on the cropped area of sorghum (excluding the first irrigation), groundnut and cotton. The results of the simulation show that there is a reduction in the deposition by 2740 $m^3$and 1360 m^3 at the first and second reaches respectively. The reductions are 34% and 40% compared to the actual situation.

5.4. *Scenario 2. Operation based on crop water requirement*

The sediment was simulated based on the crop water requirement (CWR) at the period of high sediment concentration between 10 July and 10 August, since there was more sediment inflow to the scheme during this period as shown in figure 3. There was more sediment load inflow to the scheme during this period in 2011 as a result of more water delivered. The aim of this scenario is to mitigate as much as possible the inflow of sediment during the high concentration period and to address the effect on the deposition. The inflow at the offtake was computed based on the crop water requirement by considering all the losses. The inflow during that period reduced from 11.5 Mm3to 4.86 Mm3 based on CWR (57.7% reduction inthe inflow). Consequently, compared to the actual flow the sediment volume was reduced by 51% in the first reach and by 55% in the second reach. The predicted bed profiles according to the different options of operation are presented in figure 5.

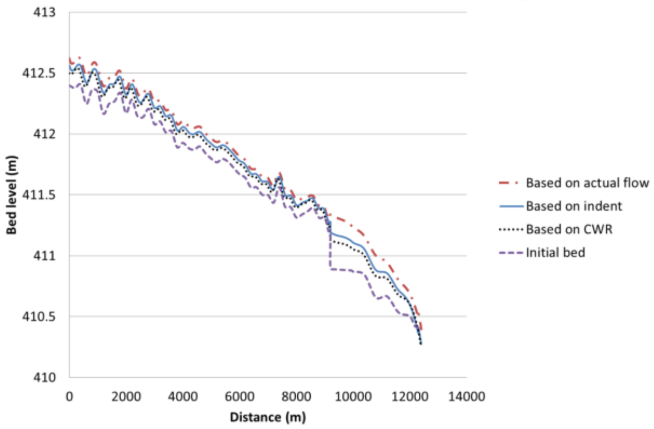

Fig.5: Simulation of sediment based on crop water requirement at the period of high sediment concentration, the predicted bed based on the indent system and based on actual flow

5.5. *Operation under future changed conditions*

A hypothetical case has been applied to predict the deposition in Gezira Scheme in case of reduction in the sediment concentration as a result of the operation of the Grand Ethiopia Renaissance Dam or any improvement in the soil conservation upstream the Blue Nile Basin. This is a new dam constructed by the Ethiopian Government across the Blue Nile River near the boundary of Sudan. According to [10] the sediment concentration is expected to be reduced as a result of this dam. The aim of this scenario is to address the effect on the sedimentation in the Gezira Scheme if the sediment concentration of the Blue Nile River would reduce by 50%. The results of the simulation of the suspended sediment transport in the major canal indicates that the deposition at the first and second reaches will be 2600 m^3 and 953 m^3 which presents respectively 74% and 81% reduction in the deposition, when compared with the actual situation in 2011. Figure 6 demonstrates the increase in bed level at the off-take of the major canal based on reduction of the concentration by 50% and based on the actual situation. This implies that improvements in the land use and water management practices upstream of the Blue Nile Basin may also reduce the quantity of sediment entering the scheme. Table 2 summarizes the deposition for the different options of operation for the first and second reaches of Zananda Major Canal.

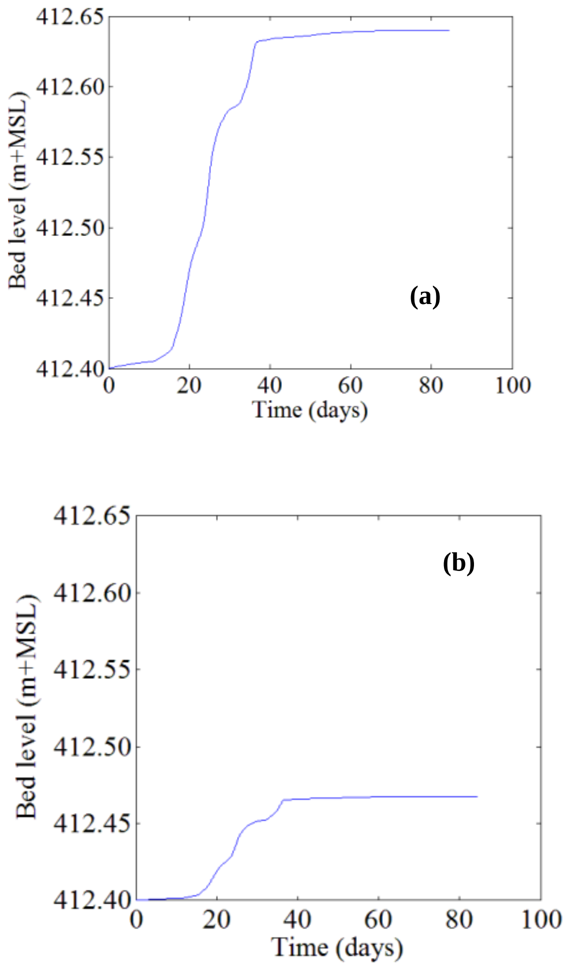

Fig. 6: Accumulation of the sediment at the offtake of the major canal based on reduction of concentration by 50% and on the actual situation,(a) Reductionofconcentrationby50% , (b)Actualsituation

Table 2: Canal siltation in (m^3) based on different options of operation by using 2011 data

Operationscenarios	1st	2nd
Actualflow	9160	4370
Indentsystem	6010	2620
ApplyCWRduringhighconcentrationperiod	4510	1970
50%reductionin concentration	2410	832
Design bed profile withindentsystem	11400	4540

6. CONCLUSION

The FSEDT model is a useful tool to simulate the cohesive sediment transport in irrigation canals. Furthermore, it can help the operators and decision makers to develop strategies for effective sediment and water management. The model has been calibrated and applied in Gezira Scheme but it could also be applied widely at cases similar to Gezira Scheme. The simulation of the sediment transport in the irrigation canals based on different operation scenarios shows that the current operation system leads to high sedimentation in the canals since no systematic operation rule is currently followed.

To adjust the water supply during the period of high sediment concentration based on the crop water requirement contributes significantly in improving the water delivery performance and reduction of the deposition. For effective sediment and water management, it is recommended to operate the scheme based on the crop water requirement at the period of high sediment concentration. The hypothetical scenario shows the reduction of the sediment concentration of the Blue Nile River has its significant effect on the reduction of deposition in the irrigation canals.

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