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Mitigation of Sedimentation at the Diverstion Intake of Fota Spate Irrigation: Case Study of the Gash Spate Irrigation Scheme, Sudan

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Abstract

Blocking of diversion intakes and canals by sediment deposition is a widespread problem in many spate irrigation (flood water farming) systems. In the Gash Spate Irrigation Scheme (GSIS), particularly the Fota block, sedimentation is a continuous challenge that resulted in 75% reduction of the irrigable land (2012 data). The scheme receives sediment laden flood water from the Gash River which originates from the Eritrea-Ethiopia Plateau. The GSIS is the breadbasket for the Eastern Region of Sudan with over half a million inhabitants. This research focused on sedimentation problem and its remedial measures at Fota diversion intake. The sediment deposition in front of Fota diversion intake reached up to 1.5 m depth. This deposition at the diversion intake plus sedimentation in the canal networks reduces the Fota block irrigable land by 75%. Therefore, providing remedial measures to the sedimentation problem at Fota intake would directly impact the livelihood of 100's of poor farmers. The sedimentation at the vicinity of the diversion intake was analysed using a Delft3D model. The model was calibrated and validated using observed water levels at Fota diversion intake, with a coefficient of determination (R2) of 85% and 72% respectively. The model result under existing condition showed a 1.6 m sediment deposition at the main intake which in fact is the real situation on the ground. Alternative, sediment remedial measures based on local knowledge of farmers and technicians were modelled. Sedimentation at the intake could be reduced to almost zero if additional three Spurs (100 m, 50 m and 120 m long) are constructed on the opposite bank of the diversion at 25 m, 100 m and 200 m upstream the diversion structure respectively, and increasing the intake sill level by 1 m.

Keywords: Spate irrigation; Sedimentation; Modelling; Delft3d; River morphology; Diversion intake

Introduction

Spate irrigation is a type of water management that flood water from mountain catchments, laden with sediment concentration as much as 10%, is diverted from rivers and spread over large areas. It is unique to semi-arid environment and found in the Middle East, North Africa, West Asia, East Africa and parts of Latin America [1,2]. Spate systems are very risk-prone. The uncertainty comes from both the unpredictable nature of the floods and the frequent river bed changes due to sedimentation. Sedimentation is a real challenge for spate irrigation systems at the diversion structure from the river source. In almost all cases, flood water arrive with high sediment load, and creates serious problems at diversion intakes and canals network if it is not controlled and managed properly [3,4]. Therefore, the study of sedimentation is vital aspect for planning and design of a river basin. This study could be supported by detail analysis of flow pattern and sediment transport [5]. Advisory literature suggests several interventions to mitigate sedimentation including construction of sediment exclusion, settling basin, sediment extractor, and good design of canals and also by improving the operation and maintenance practise [6]. Field-based researches on sedimentation issues are very limited and there is still a huge knowledge gap on specific remedial measures for different magnitude of sedimentation problems under different physical, institutional and economical situations. The Gash River originates from the Eritrean-Ethiopian Plateau, and ends up in a Delta in Sudan, providing spate water for the Gash Spate Irrigation Scheme. The Gash River is characterised by flashy floods, and has uncertain flow with very high sediment concentration of up to 60,000 ppm. The river course has high sediment deposition and this seems due to braided channel aggradations and lateral migration and by both channelized and un-channelized sheet flood deposition [7]. Based on previous report, annually 5.5 -13 million tons of sediment has estimated to be brought by the River [8]. The major part of this sediment deposited in the GSIS, more noticeably at the canal and diversion intake structures. The Fota diversion intake (a pilot study site) is one of the 7 diversion intakes in the GSIS, which is most affected by sedimentation. The sediment deposition in front of Fota diversion intake reaches up to 1.5 m. This deposition in combination with sedimentation in the canal networks reduces the Fota Block irrigable land by 75%. Therefore, providing remedies to the sedimentation problem at Fota intake would directly impact the livelihood of 100's of poor farmers who solely depends on agriculture. Primary and Secondary data such as river cross section, sediment samples, hydrological data, detailed design documents were collected. In addition, discussion with key stakeholders, namely the farmers and scheme managements were carried out. The Delft3D model was used to assess the magnitude of sedimentation problem. The model was calibrated and validated based on water levels at Fota intake and simulate alternative remedial measures. This paper encloses description of the study area in Section 2. Section 3 provides details about methods and data used and also schematization of the study area, Section 4 presents model scenario results and discussion and these are followed by conclusion under section 5.

The Study Area

The Gash Spate Irrigation Scheme (GSIS) is located in the eastern part of Sudan (Figure 1a). Spate irrigation has been practiced for more than a century for production of main crops such as Barley, Sorghum and Cotton in the area. The scheme is operated by the Gash Delta

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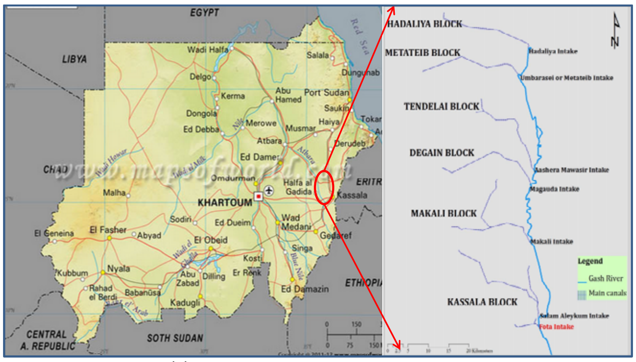

(a) (b)

Figure 1: (a) Location map **(b)** Layout of intakes and main canal along the river.

Agricultural Corporation (GDAC), and also technically supported by the Gash River Training Unit (GRTU) of the federal ministry of Water Resources [9]. The first design of the system was developed in the 1930's and improved in the late 1950's. The GSIS area is characterized by semiarid climate with two notable seasons, winter and summer. The max temperature may exceed 45°C in the summer time, and drops to an average of 25°C in the winter [10]. The Gash River, water source of GSIS, originates from the Eritrean-Ethiopia Plateau and travels about 121 Km from the border with Eritrea down to the Gash Die (end of the delta). The total catchment area of the River is 21,000 km^2 [11]. It is seasonal river, flows between late June to October, with high flows occurring between July and September. The maximum annual discharge accounts 1430 million m^3 recorded in 1983 and annual minimum flow of 140 million m^3 was gauged in 1921 [11]. Sediment concentration varies between 3000 ppm to 30,000 ppm on average, but may exceed more than 60,000 ppm during high flood. In general, the river is characterized by large variations in annual flow and heavy silt loads [12]. The total gross area of the Gash Delta is 2,80,000 ha, of which 1,00,000 ha is used for irrigation. However, the irrigated area allocated for annual rotation is about 30,000 ha [13]. The irrigation systems includes 7 Diversion Intakes, 7 Main canals (Figure 1b), and 212 messga canals (tertiary canals). All canals receive water on the left bank of the river since the terrain slopes declines in north-west direction. The area of messgas (farm blocks), which is irrigated by one tertiary canal, varies from 300 ha to 1200 ha. The flood water is diverted from the wide river through a brick structure intake (Figure 2). The Fota intake composes of 3 openings, with dimension of 2.5 m width and 3.0 m height. The intake is closed manually by timber stop loges. The Fota main canal is an earthen canal with trapezoidal cross section and side slope of 1:0.5 /1:1.2. During the flood period, the deposited sediment at Fota diversion intake excavated by a stand-by excavator so as to keep continuous water flow to the command area. This effort has, however, often not been successful for most part of the flood season since the muddy situation around the intake prevents access for the excavator. Thus, as indicated in Section 1, the Fota command area has consistently suffered from severe shortages of irrigation water.

Materials and Methodology

Methodology

Assessment of the existing sedimentation problem at the Fota diversion intake and subsequent remedial measures were analyzed using Delft3D model, which is a three dimensional model system [14]. In the following sections, a detailed account is given on the set-up and schematization of the model and its calibration and validation procedures.

Delft3D model setup and schematization: Two dimensional (2D) Delft3D model was developed to simulate the river morphodynamics around Fota diversion intake. Delft3D package, developed by WL/Deltares in close cooperation with Delft University of Technology, is a software for simulating hydrodynamic flow (under the assumption of shallow water), transport of water-borne constituents, short wave generation and propagation, sediment transport and morphological changes and ecological processes and water quality parameters [15,16]. The model uses three basic equations to study the sediment transport process these are: Continuity equation, Momentum equation and Transport equation [14]. A reach of 10 km length of the Gash River was schematized in Delft3D model using 2856 grid cells (Figure 3). It starts from Kassala Bridge (upstream boundary condition, BC) and ends at Salamalikum (downstream BC). The upstream BCs are measured discharge and sediment load at Kassala Bridge station. The downstream BC is taken as the water level and sediment load measured at Salamalikum station (Section 3.2). Then the model was calibrated and validated using measured data at Fota diversion intake which is 7 km far away from Kassala Bridge (upstream BC). Based on the river cross section data (Section 3.2) and extent of the river boundary, a

Figure 2: Sedimentation affected Fota diversion intake.

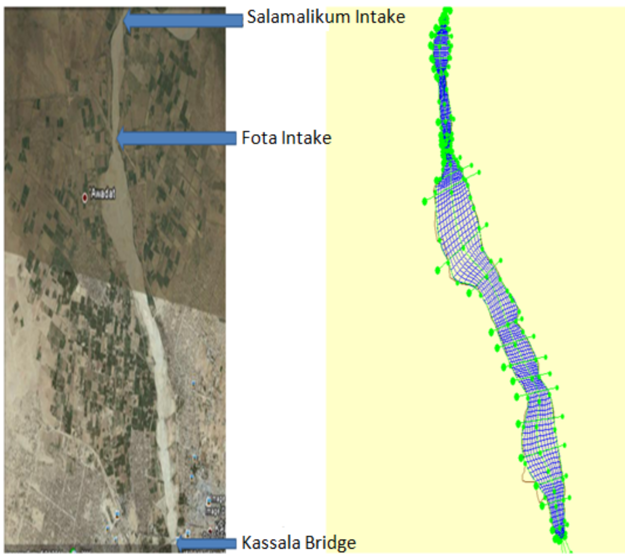

Figure 3: Developed spline, grids, and bathymetry for Gash River.

numerical grid and bathymetry of the river were established. The grid orthogonalized and smoothed to reach representative schematization of the flow pattern in the study area. The generated grids for the river have the following properties:

- Grid points in M direction is 204.
- Grid points in N direction is 14.
- Maximum and Minimum Grid size in M direction is 125 m and 1.5 m respectively.
- Maximum and Minimum Grid size in N direction is 84 m and 2 m respectively.
- Orthogonally for the whole grids ranges from 0 to 0.14, however most of, around 95%, is fall below 0.01.
- Smoothness in M direction for the whole grids ranges from1 to 3.73, however most of, around 98%, is fall below 1.14.
- Smoothness in N direction for the whole grids ranges from1 to 2.75, however most of, around 95%, is fall below 1.18.
- Aspect Ratio for the whole grids ranges from1 to 9.64, however most of, around 90%, is in the range of 1to 1.8.

The Flow module was used to enter all required data (Section 3.2) and physical parameters (Table 1) in to the Delft3D model system. The model simulation results were calibrated and validated hydrodynamicaly and then calibration of sediment transport proceeded.

Materials

Boundary condition: The River Gash has 5 gauge stations, since the model was developed within the three gauge stations, namely Kassala Bridge, Fota and Salamalikum, all available measured data from those three gauge stations were collected. Since the available data have lots of missing values, well completed daily data of year 2005 and 2006 were used to calibrate and validate the models respectively. The discharge and water level used for boundary condition for the models for 2005 and 2006 year data are shown below in Figures 4 and 5. For some missed data, a data driven graph was developed and used to fill the missing values. Sediment concentration measurement in Gash River started from 2004; however there was a lot of missing data and discontinuity in measurements. After 2008 the measurement of sediment concentration at Fota and Salamalikum station also interrupted [3]. For this study, measured silt and clay concentration is used. For the case of sand concentration it is assumed that the flow enters at the Kassala Bridge with equilibrium sand concentration. This is because of two reason: the first one is the available data on the sand concentration is very limited and the second is since the flow reaches to the Kassala Bridge travelling long distance it could attain equilibrium flow for sand concentration. Based on this, the sediment distribution of the area was studied and mitigation measures were provided. For the analysis of sediment grain size of the River, 7 deposited sediment samples from different points

Physical parameters used in the model	Values
Chezy Roughness	50 $m^{1/2}/s$
Sediment transport predictor	E-H
Morphology factor	1
Courant number	10
Time step	0.05 minutes
Horizontal eddy viscosity	1 m^2/s
Horizontal eddy diffusivity	0.1 m^2/s

Table 1: Model parameters.

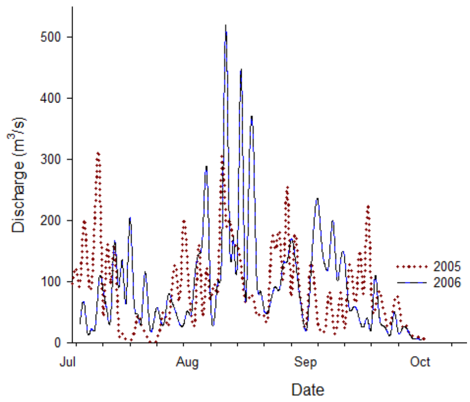

Figure 4: Daily discharge hydrograph at Kassala bridge (Upstream BCs).

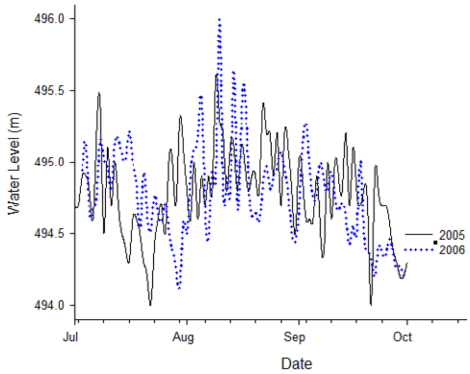

Figure 5: Daily water level hydrograph at Salamalikum (Downstream BCs).

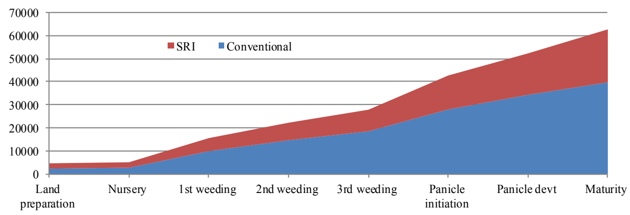

Figure 6: Mean sediment grain size analysis.

of the River bed were collected. Random sediment samples collections were done within the range of 50 m to 500 m interval between sample points. The d50 of the river bed material (after flood season) for the samples ranges from 220 μm to 280 μm (Figure 6). The sediment particle density of the sand samples in Gash varies from 2500 Kg/m³ to 2640 Kg/m³. Therefore, an average value of 2550 Kg/m³ was used. Since there was no information available on settling velocity of the Gash sediment, settling velocity from Gezira scheme which has more or less similar sediment source catchment area were used.

Topographic surveying: The 14 km length of the Gash River Cross Section was surveyed in 2004 by the GRTU. Therefore, this secondary data were used to develop the river bathymetry from Kassala Bridge to Salamalikum gauge station. In the field observation, the area around the Fota diversion intake shows a serious sedimentation problem. The elevation of the Fota intake bed level is 494.87 m.a.s.l and the crest level

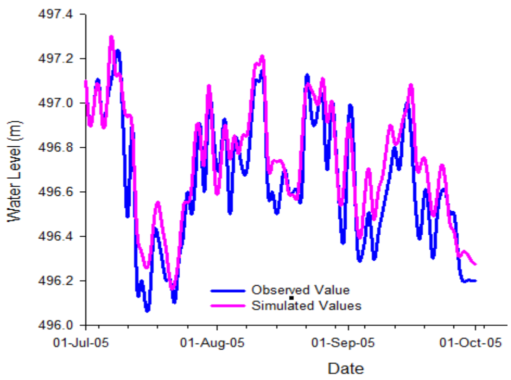

Figure 7: Daily water level for observed and simulated at Fota gauge station (2005).

of the diversion headwork/weir downstream of the intake, which is by now completely buried, has an elevation of 496 m.a.s.l. This creates about 1.13 m sediment to be deposited easily around the intake. In addition to the river cross section primary data on-length and location of existing structures/spurs was collected.

Operation and maintenance: Information's on the operation and maintenance of the Fota intake was collected from the Gash Agricultural Scheme Authority (GASA). It shows that they used a stand-by excavator near the diversion intake during irrigation period for removing sediment deposited at the intake and the most upstream part of the main canal so as to allow water flow in to the irrigation system. Due to the sediment deposition, the Fota irrigation system gets water only during high flood time.

Results and Discussions

Calibration and validation of Delft3d model

The Delft3D (hydrodynamic) model was calibrated using the available measured daily data of the Gash River water levels during 2005 at Fota Diversion Intake. The comparison of daily average water levels is shown in Figure 7. The coefficient of determination R^2 between simulated and observed water level was found to be 0.74. The observed discharge values at Fota gauge station showed a bit strange values for the period August 5, 2005 to August 15, 2005. Excluding these values led R^2 improved to 0.85. However, it couldn't be confirmed that these data were wrong. As shown in the Figure 7 there is somewhat over estimation by the model especially around August 8-20/2005 and also during pick flow. The validation results of the hydrodynamic model using 2006 year data are given in Figure 8, few outliers of the observed data (12 days) were excluded, and then R^2 found to be 0.72. As portrayed in the Figure 8, the simulated values shows poor fit for peak and low flow. This might be due to the data quality, however it follows similar trained as the observed one. Since there was no continuous sediment deposition data around Fota Diversion Intake for model calibration, qualitative calibration (sedimentation pattern) and total depth of sediment deposited on the sill of the intake (sill level is 494.87 m.a.s.l. and deposited sediment level is 496.27 m.a.s.l.) was adopted. As shown in the Figure 9 below, the sediment deposition near the intake is high and causes the water main channel to flow far away from the diversion intake (see the real condition under Figure 2 left top picture). The intake was buried by more than 1.5 m sediment deposition. This is a real situation in the area and results in limited water inflow to Fota Main Canal only during high flood time.

Comparison and sensitivity analysis

A comparison of the sediment transport equations (Van Rijn and Engelund and Hansen, E-H) were carried out to investigate the applicability of the sediment predictor equation for the Gash River. The analyses indicated that Van Rijn transport equation computed a very high sediment deposition around the diversion area than both the existing condition and E-H transport equation result (Figure 10a). Model sensitivity was also investigated for varying Chezy roughness coefficient (50 $m^{1/2}/s$ and 40 $m^{1/2}/s$), as well as for different sediment particle size, d50 (225 μm and 270 μm). The result shows that the change in roughness coefficient has less effect on the sedimentation patterns. On the other hand, Chezy with 40 $m^{1/2}/s$ provides relatively low sedimentation on both sides of the river banks around the diversion intake (Figure 10b). In the case of sediment particle size, the sedimentation pattern has less effect as is the case with roughness coefficient. However, with large sediment size, relatively high deposition occurs upstream of the diversion intake (Figure 10c).

Model scenario analysis

To assess the sedimentation problem in the area and suggest mitigation measures, three scenarios were evaluated:

Existing condition (baseline scenario)

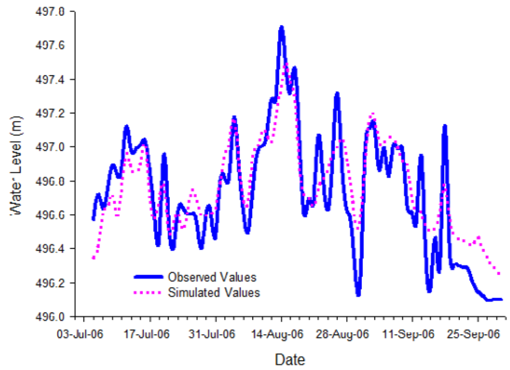

Figure 8: Daily water level for observed and simulated at Fota gauge station (2006).

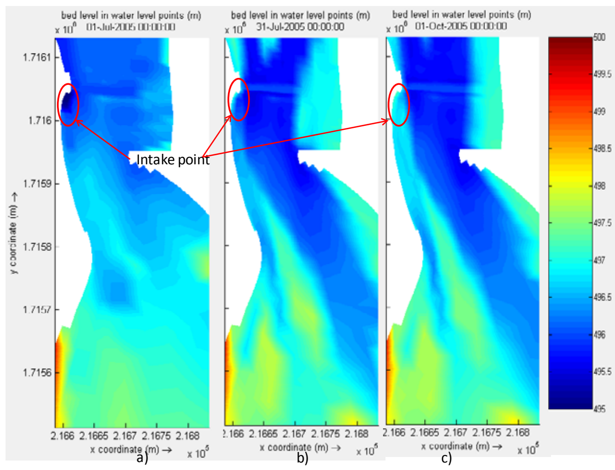

Figure 9: River morphology change at Fota diversion intake: (a) at the beginning, (b) after 1 month and (c) after one year simulation.

1. Constructing 200 m long guiding wall in the right side of the Gash River around the diversion intake area (Figure 11a)

2. Constructing 3 spurs in the right side of the Gash River around the diversion intake area and increasing the intake sill level by 1.2 m (Figure 11b)

For the existing condition (Figure12), the simulation showed high sedimentation (more than 1.5 m depth) at the diversion intake which diverts Gash flow away from the intake. The design bed level of the intake structure is 494.80 m.a.s.l, while there is a diversion weir across the Gash River with a crest level of 496 m.a.s.l. which is located at 5 m downstream of the intake structure [17]. This actually favours 1.13m sediment deposition at the intake during flood. In case of both scenarios (scenario 2 and 3) (Figures 13a and 13b), the model results showed reduction of sediment deposition around the intake. This is mainly because both interventions reduce the river flow width which leads to higher flow velocity and hence increase the sediment transport capacity. The introduction of spurs (scenarios 3) has outperformed than guiding wall (scenario 2). While the former resulted in almost zero sediment deposition, the latter could only reduce sedimentation from more than 1.5 m (under existing condition) to 0.8 m. Figure 13a, 13b and 13c provide the illustrations. The construction of spurs has additional value of creating open space on the right bank of the river for sediment deposition. As a result the downstream part of the river will not be affected by excess sediment removal from the diversion intake.

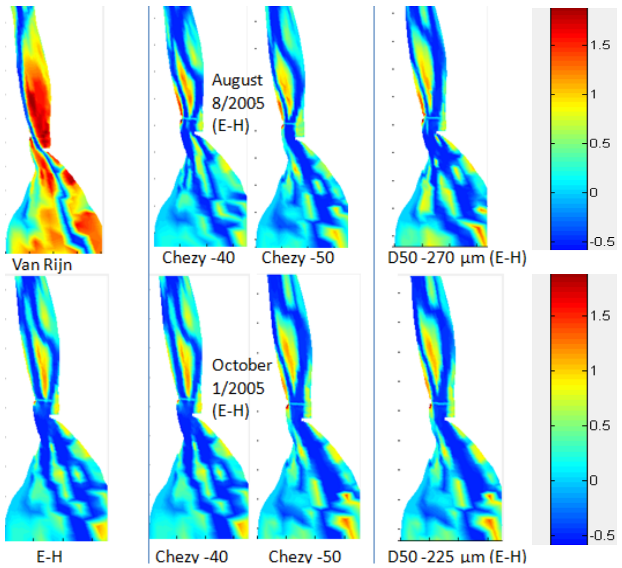

Figure 10: Comparison of sediment transport equations (a), and roughness (b) and sediment particle size (c) sensitivity.

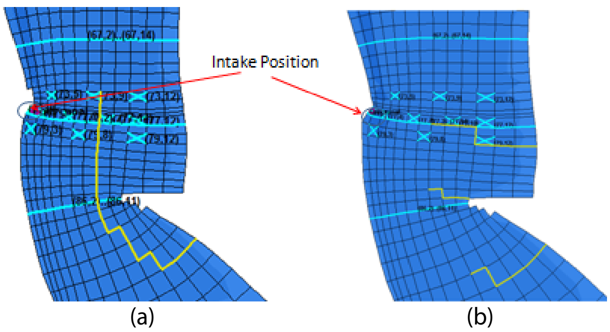

Figure 11: Proposed sediment mitigation mechanisms at the Fota intake: a) guiding wall and b) spurs.

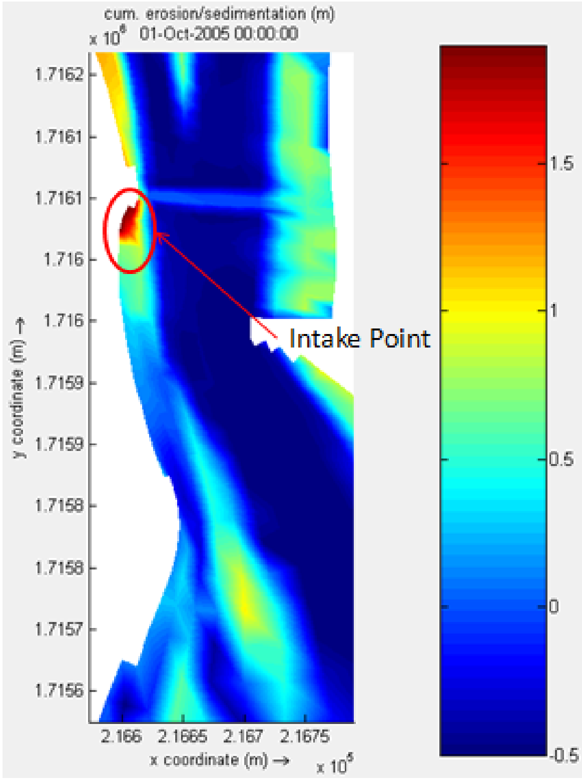

Figure 12: Simulated (existing) cumulative erosion/sedimentation around Fota intake.

Conclusion

The research conclude that under existing condition, more than 1.5 m of sediment annually deposited and this deposition completely block the water inflow into the Fota main canal system. The deposition is attributed mainly to a weir constructed just downstream the intake, which is 1.13 m higher than the bed level of the intake, and the wide river water flowing width near to the intake. Introducing a 270 m length guiding wall reduces the river flow width near the intake, increases the sediment transport capacity thereby reducing the sediment deposition at the intake to 0.8 m depth (scenario 2). Constructing groyens/spurs (scenario 3) on the right bank of the river combination with intake modification (constructing sill with 1 m height at the intake) could almost completely avoid sediment deposition at the intake. Engelund-Hansen sediment transport predictor equation provides better result for the Gash River compared to Van Rijn equation. The sediment deposition predicted by Van Rijn equation is over estimated. It shows more than meter depositions all around the diversion weir and intake which is not the situation in the study area. Using the Engelund-Hansen sediment transport predictor equation the sensitivity of the model for change of roughness coefficient and sediment particle size was evaluated. Change of sedimentation pattern found to be less sensitive to changes of roughness coefficient and sediment particle size. However, the sediment deposition upstream of the diversion intake increases with increase of sediment particle size.

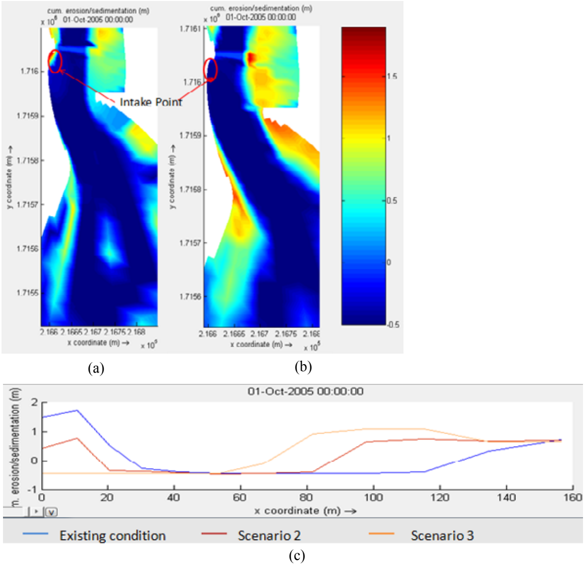

Figure 13: (a) Cumulative sedimentation/erosion for guiding wall, (b) spur/ groyens intervention and intake sill height change and (c)comparison of the three conditions.

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