Optimizing Flood and Sediment Management of Spate Irrigation in Aba'Ala Plains

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Abstract

Floodwater management and sedimentation are the key issues which should be considered during the development of new, or improvement of existing, spate irrigation schemes. The traditional intakes are superior in their site location, flexibility, and sediment-control capability. However, they have been frequently damaged by floods resulting in loss of continuous irrigation supply. The modern structures, albeit strong enough to withstand the impact force of the largest floods, suffer from large sedimentation problems. Farmers of Aba'ala Plain have been struggling with sedimentation and floodwater-management problems associated with their modern and traditional intakes. The objective of this research is, thus, to study the existing flood and sediment management practices and identify alternative options for optimum management of floods and sediments in the Aba'ala Plain, Afar. Aba'ala is the largest plain in the arid lowlands of Ethiopia where a combination of traditional, improved and modern spate irrigation systems are practiced. Extensive fieldwork was undertaken leading to measurement and collection of primary data including discharge, sediments and river cross sections. Interviews and focal group discussions were also employed and these generated deeper insights into O&M activities. In addition, Alluvial Friction Predictor and Sand Transport Predictor of SHARC model were employed to generate sediment concentration of the floodwater. Delft3D, a hydrodynamic model, has been used to simulate flow patterns and sedimentation under the existing condition and for different improvement options. For the existing condition (scenario-I), results of the model simulation showed high sediment deposition and low floodwater abstraction rate. Consequently, only 41 and 23% of the command areas under the modern and traditional intakes can be fully irrigated during the bad flood season. The high intake diversion rate and the reduced sedimentation around the intake were achieved with the improvement options under scenario-II (four consecutive bed stabilizers, a 30 m guiding wall upstream of the modern intake and reinforcement of the traditional intake). However, this scenario has a potential to cause conflict between upstream and downstream users as the result showed a decline of water level (15 cm) at the downstream intake. Therefore, scenario-III is recommended for a maximum floodwater diversion and minimum sediment deposition with a fair share of water between upstream and downstream intakes. This scenario would consist of open gabion reinforced multiple intakes with a 78 m long guide wall upstream of the modern intake, a 30 m long guide wall upstream of the traditional intake and a series of four bed stabilizers upstream of the diversion point.

Key words: *Spate irrigation, flood, sedimentation, intakes, canals, Delft3D, optimizing, modeling*

1. Introduction

The arid lowlands of Ethiopia form one of the most vulnerable and food-insecure regions in the world. Out of a population of 11 million, about 3.4 million who live in the arid lowlands of Ethiopia depend on food aid. Droughts in the years 2000, 2005, 2008 and 2011 raised the number of food-aid dependent people to 5.7 million in 2011. As the results of the droughts during those years, distress sales of livestock and other assets was a common phenomenon in the areas affected by the drought (Mehari et al. 2013). Aba'ala, located in the arid lowland area, had been affected by severe droughts and famine for years (Kifle 2004). There is no perennial water source to support crop production in the area. However, Aba'ala receives intense short-duration floods coming from Didiba Derga-Ajen highlands in Tigray Regional State. Efficient and effective diversion and distribution or storage of the floodwater would make water available in Aba'ala Plain that is inhabited by agropastoralists. Spate flow was considered to be the most economical and the only resource of water for crop production (spate irrigation), livestock production and domestic uses.

Spate irrigation is one type of water management applicable to arid regions bordering highlands. It is a largely neglected and forgotten form of resource management, in spite of its potential to contribute to poverty alleviation, adaptation to climate change and local food security (Steenbergen et al. n.d.). Tesfai and Sterk (2002) defined spate irrigation as runoff farming that makes use of floods originating from episodic rainfall in macro-catchments in the highlands, which are diverted by temporary or semi-permanent structures to irrigate fields.

In the Aba'ala Plain, both traditional and modern spate irrigation systems are practiced, in which short-duration floods with large discharge are used to irrigate land by spreading floodwater across cropland, rangeland or dryland-forest. In some cases, the floodwater may be used to recharge shallow groundwater, which makes it possible to tide over a drought period and make use of the floodwater (Mehari et al. 2011). Managing the floodwater is the major challenge to make spate irrigation sustainable and productive for reasons such as occasional large volume, destructiveness and high sediment load.

The traditional diversion structures and canals in Aba'ala Spate Irrigation scheme were frequently damaged by large floods. The farmers in the area have for years struggled to rebuild the intakes and water distribution structures on time to make efficient use of subsequent floods. Their effort in this daunting task had been an exercise in futility; several flood use opportunities were lost due to failures to maintain and sustain the structures. Consequently, limited soil moisture (moisture stress) contributed to poor crop stand and yield, a common phenomenon in the Aba'ala Plain.

Spate irrigation is as much about sediment management as it is about water management (Van Steenbergen et al. 2010). Spate flows usually carry high sediments, which deposit around diversions blocking intakes and canals or are transported to the fields causing rapid rise of the command areas. However, it should be noted that these sediments can be a source of valuable plant nutrients that maintain soil fertility (Tesfai and Sterk 2002; Lawrence 2008; Van Steenbergen et al. 2010).

There was no serious problem associated with sediment under the traditional system since much of the sediments at the vicinity of the structures is washed away during high floods. Moreover, a study made by Lawrence (2008) too indicated that traditional intakes were less affected by sedimentation than the modern intakes; they are washed away by the large volume and high velocity of floods when the concentration of coarse sediments is high.

In Aba'ala spate irrigation schemes, the problem of sediment deposition is more pronounced with modern diversion and intake structures. The effort made to modernize the scheme was focused on increasing volume of diverted floodwater without due attention to the sediment deposition at the vicinity of the structure and the resulting negative effect on the level of abstraction and structural deterioration and damage to the same. Moreover, the scouring sluices have never operated since the construction of the scheme; the above issues combined with poor design of the diversion weir (conventional irrigation type design) led the structure to be completely filled with sediments in a single flood.

In general, lack of sediment control and inefficient management of floodwater are the two major and serious problems that farmers at Aba'ala Plain face in sustaining crop and livestock production under spate irrigation.

The failure and inadequate functioning of the diversion and intake structures have made floodwater and sediment management problems common and persistent in the entire canal network and the irrigated fields. The poor design that channeled floodwater to one or at most to two canals at the headwork also exacerbated the sedimentation problems. Lack of operational rules for the scheme has seriously affected the effective and efficient (uniform water distribution) utilization of floodwater. Furthermore, efforts made to manage floodwater and control sedimentation to date, have been structural. The government and donor organization(s) that effected the construction of the structures never analyzed and learned lessons about the possibilities of alternative spate irrigation system options with regard to layouts, structural designs, operational strategy, rules and regulation on floodwater use, and exit strategies.

Re-examination of the current practice of spate irrigation in order to develop alternative solutions to the problems faced is the order of the day: to make effective practice of spate irrigation (through efficient layout, remedial work, proper construction, adoption of locally maintainable structures); considerations of alternative years/seasons (good, or moderate or poor flood year/season); and different scenarios (as is, required changes). Hence, this study was undertaken with the following objectives:

1. Major objective: To identify alternative options that would optimize floodwater and sediment management in the Aba'ala Plain where spate irrigation is practiced as a major means of food security.

2. The specific objectives:

- To determine the flood discharge and rate of sediment deposition at and around the intakes.
- To evaluate the design of traditional and modern diversion and intake structures in light of sediment management.
- To evaluate the adequacy of diverted floodwater to meet water requirement of crops grown under the scheme considering good, moderate, and poor year/season.
- To simulate and recommend suitable design options (improvements) for efficient and effective floodwater and sediment management.

2. Materials and Methods

2.1. The Study Area Location

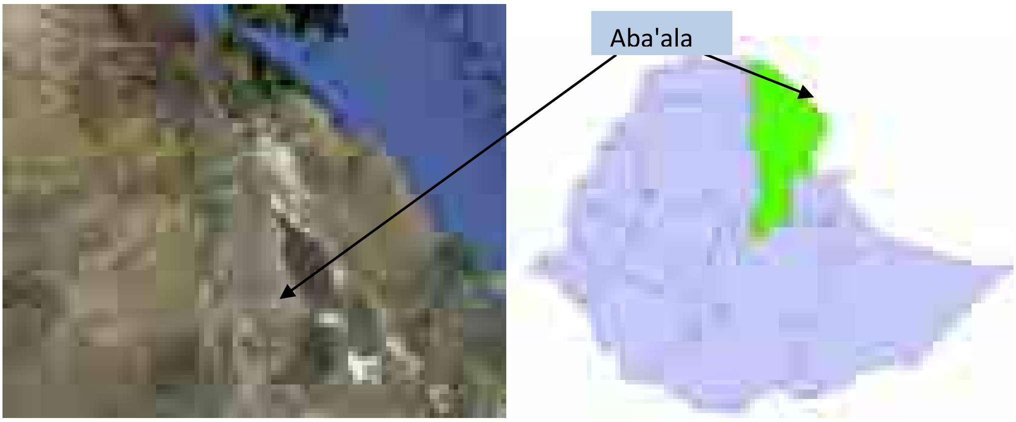
The study was conducted in Aba’ala Woreda, in Afar National Regional State, located between 130 15’ and 130 30’ N latitude and 390 39’ and 390 53’ E longitude (Figure 5.1). The major part of the Aba’ala Woreda is an extension of the rugged escarpment of the Rift Valley, which runs from north to south bordering Tigray. The woreda under the study covers an area of 1,700.00 km^2 approximately, and has a total population of 37,963 (20,486 males, 17,477 females) (CSA 2007).

2.2. Climate, Land Use and Topography

Aba’ala has a semiarid climate with a maximum temperature of 33.00 °C occurring in June and a minimum temperature of 11.60 °C occurring in November.

The study area receives a bimodal rainfall ranging from 315 to 450 mm.year^{-1} (with an annual average rainfall of 340 mm). The main rainfall takes place in a short period of time, three to four hours, with heavy storms lasting a few days, and this is followed by droughts during the critical periods of crop growth (Kifle 2004). The long rains usually occur from mid-June to mid-September. The short rains usually come in March and April.

Figure 5.1. Location of study area.



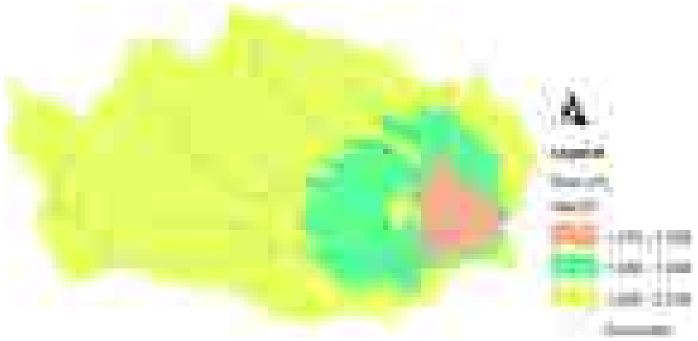
Diress et al. (2003) classified the land use of the area into 93.00% of grazing lands, 5.50% cultivated land, 1.20% wasteland and 0.53% riparian. Thirty three per cent of Aba’ala Woreda is floodplain of which 16.80% is under cultivation. The remaining 67.14% is ridges and hills mainly used for grazing or browsing.

The study area consisted of flat plains occasionally intercepted by hills and a series of elongated ridges surrounded by high broken hills with very few outlets joined to the other areas (Abebe and Solomon 2012). The altitude of the area varies from 1,300 to 1,700 meters above sea level (m asl) with an average elevation of 1,500 masl (Addis et al. 2001).

2.3. Water Resources

There are four rivers, two perennial and two seasonal, that supply water to the study area. May Shugala and May Aba’ala are the main perennial rivers, while Murga and Liena are seasonal rivers. The highland of Didiba Derga-Ajen, Tigray, with an annual rainfall ranging from 450 to 750 mm, is the main source of flow for all streams and recharges both surface water and subsurface water in the Aba’ala area (Kifle 2004). According to Abebe and Solomon (2012), Aba’ala Subbasin (UTM 596,184.8 E and 1,475,931 N) with a total area of about 55,470 ha is situated in two regions; the upland where the floods originate, highlands of Tigray Region, and the low-lying plain where spate irrigation is being practiced in the Afar Region (Figure 5.2).

Figure 5.2. Aba’ala Subbasin with the plains marked green.



2.4. Irrigation and Agronomy

Though the duration is short, the intensity of rainfall in the area is usually high leading to a large volume of runoff. However, the high rate of evaporation makes the available rainfall water insufficient to sustain crop growth, flowering and seed formation and maturity (Addis et al. 2001). Therefore, the agropastoralists in the Aba’ala Woreda depend heavily on the floodwater coming from the highlands of Didiba Derga-Ajen to grow and produce crops. Floodwater is diverted to the farmland through either temporary diversion structures (traditional), improved (gabion) or modern (concrete). During the study period, there were more than 30 primary canals supplying floodwater to the Aba’ala Plains for a variety of crops such as sorghum, maize, barley, teff, enguaya and sebere (local beans).

Two diversion intakes, meant to irrigate two separate areas of 176 and 140 ha, both located at May Shugala River, were selected for this study. The traditional diversion intake was made of earthen materials, stones and brushwood, while the modern intake was made of concrete (Figure 5.3).

Figure 5.3. Modern diversion weir (left), traditional diversion before maintenance (right).

2.5. Data Collection and Analysis

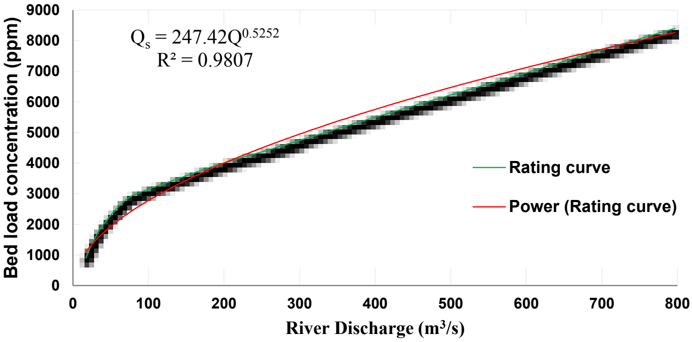
2.5.1. Riverbed Material

To develop the grading curve of the sediment bed-material and to determine mean value of D84, ten separate sediment samples were taken from four cross sections at different locations along the river route. The samples were taken in such a way that they represent low-flow canals, areas of sediment deposition and areas of erosion. Since the surface of the riverbed was dominated by coarse bed-material with wide variability in size, samples were taken by digging a pit to a depth of 1 m with cross-sectional area of 1 m^2. Size classification of bed-material was partially accomplished in the field through hand sieving to separate large materials, while separation of fine-grained materials was made in the laboratory (Figure 5.4).

Figure 5.4. Separation of sediments into different size classes in the field and laboratory.

Sediment concentration was generated using sand transport predictor, DORC module SHARC software package. Comparison of the different alluvial friction predictors made with the observed values indicated that van Rijn alluvial predictor had best fits with the observed values; thus this was used to generate depth and velocity values for the sediment concentration calculation. Sediment concentrations at different discharges gave the sediment (bed-load) rating curve shown below (Figure 5.5).

Figure 5.5. Sediment (bed-load) rating curve.



2.5.2. River surveying

Field survey was made using Total Station Method to collect data associated with the longitudinal and cross-sectional dimensions of the river. The surveying covered a distance of 1.50 km along the length of the river route. Measurements included 11 cross-section elevations along the entire length of the flood route.

2.5.3. Discharge

2.5.3.1. Floodwater discharge and hydrographs

As all the rivers were not gauged, the estimation of discharge was based on flood mark information collected from young, middle-aged and elderly farmers in the study area through interviews, and joint measurements of the height floods reached during good, moderate and bad years or seasons during field visit.

To generate floodwater discharge rates, measurements made, calculated values from the measured parameters, such as mean river cross section, wetted perimeter, mean slope, mean D84, and appropriate coefficients together with Manning's and Bathurst Equations were employed; The used equations are given below.

$$Q = \left(\frac{1}{n}\right) \times A \times R^{0.67} \times S^{0.5} \quad \textit{(Manning Eq.)} \tag{2.1}$$

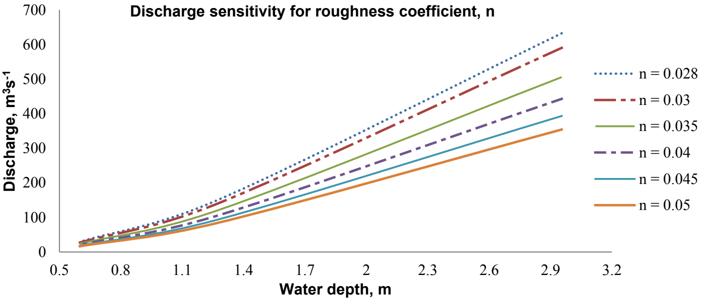
$$Q = A \times D^{*} \times (gRS)^{0.5} \quad \textit{(Bathurst Eq.)} \tag{2.2}$$

$$D^{*} = \left(5.62 \times \log\left(\frac{d}{D_{84}}\right) + 4\right)$$

Q = Discharge
A = Cross-sectional area
R = Hydraulic radius
S = Slope
n = Manning roughness coefficient
D* = Particle parameter
g = Acceleration due to gravity
d = Mean flow depth (approximately the same as the hydraulic radius, R)
D84 = Size of the bed material for which 84% of the material is finer (m)

However, it is recommended that the roughness coefficient be estimated using D84 value of the riverbed material along the slope area reach (Arcement and Schneider 1989) due to the very fact that the discharge computed using Manning's formula is highly sensitive to roughness values especially at increased water depths (Figure 5.6).

Figure 5.6. Sensitivity test for roughness.

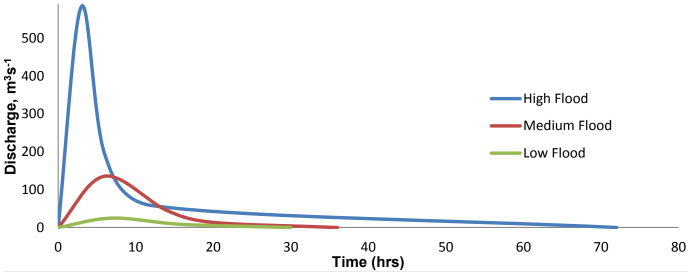


The value of Manning Roughness coefficient (n) for gravel bed rivers ranges from 0.028 to 0.05 (Arcement and Schneider 1989). From sensitivity analysis, it was found that the discharge computed using Manning's formula was highly sensitive to roughness values. Hence, Bathurst formula, which considers the D84 to estimate the riverbed roughness, was selected for further investigation during the course of this study, thereby minimizing the uncertainties in using Manning's formula.

2.5.3.2. Hydrographs

Flood hydrographs were required to develop time series flow data which will be used in Delft3D model. In addition to the flood marks, the time to peak and time to end of the high, medium and low floods were identified during the interviews made with the farmers. According to the suggestion of Wateryemen.org (2003), a standard hydrograph for rivers with mountainous catchments is characterized by a time constant where it is changed (increased) when the discharge declines to one-third of the peak, and again when the discharge declines to one-tenth of the peak. Hence, combining the data collected during farmers' interview and the suggestion made (Wateryemen.org, 2003), an incoming flood hydrograph shown in Figure 5.7 had been generated for the river.

Figure 5.7. Actual spate flow hydrograph.



2.6. *Desired Discharge at Intake and Canals*

The discharge desired at the intakes was estimated by considering the type of crops grown, total command area of the intake, irrigation rotation and the irrigation time. Focal group discussions and collection of x, y coordinates of points bordering irrigation fields were carried out to identify the type of crops grown, irrigation rotation, and size of command areas. ArcGIS was employed to develop a map of the scheme (Figure 5.8) with details of the command area for each canal.

Figure 5.8. The traditional and modern diversions with their canal network.

The rate of discharge required at each secondary canal offtake was calculated by taking a maximum seasonal crop water requirement of three crops: sorghum, maize and pea (Brouwer and Heibloem 1986). The gross seasonal water requirement of sorghum, maize and pea was calculated to be 1,300, 1,600 and 1,000 mm, respectively. Irrigation time was selected considering indigenous farmers’ practice and the number of floods occurring during the bad and good seasons. Table 5.1 shows the required discharge to meet the water requirements as calculated following standard procedures.

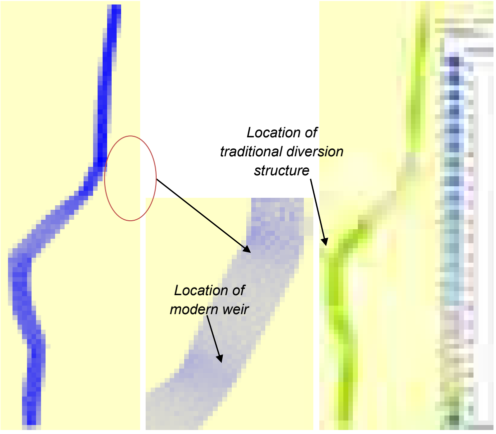
Table 5.1. Required discharge calculation on the basis of crop water requirements of the canals.

Name of Intake	Name of Canal	Area (ha)	Irrigation time (hour)	Required Q in m3/s (Bad season)		
				Sorghum	Maize	Pea
Gira Mahber	Mesgid	51.00	48.00	3.84	4.72	2.95
	Abo Amin	22.00	48.00	1.66	2.04	1.27
	Halefom Hadush	8.00	48.00	0.60	0.74	0.46
	Abo Adhana	31.00	48.00	2.33	2.87	1.79
	Demsash	56.00	48.00	4.21	5.19	3.24
	Via Scouring	8.00	48.00	0.60	0.74	0.46
	Total	176.00	-	13.24	16.30	10.19
Berhe Afle	Gira Fitsum	47.00	48.00	3.54	4.35	2.72
	Berhe Afle	31.00	48.00	2.33	2.87	1.79
	Berhe Keshi	12.00	48.00	0.90	1.11	0.69
	UN	5.00	48.00	0.38	0.46	0.29
	Demsash	42.00	48.00	3.16	3.89	2.43
	Total	137.00	-	10.31	12.69	7.93

2.7. Model Setup

To simulate the floodwater flow and sedimentation patterns along the river the Delft3D-RGFGRID model was set up for a river reach of 1.5 km length. In order to clearly observe the floodwater flow and sedimentation patterns grids around the diversion intakes were further refined locally. The quality of the generated grid was checked against the grid quality standards, like orthogonality and aspect ratio, in order to eliminate computational errors during model simulation. The grid was then edited until the desired orthogonality and smoothness were achieved. Finally, staggered grids of good quality with orthogonality values ranging from 0 to 0.07 (more than 98% lying below 0.04) and aspect ratio values of 1.0 to 1.98 were obtained to be used as a domain in the model simulation (Figure 5.9).

Figure 5.9. Generated grid for the river (left and middle) and its orthogonality (right).



The hydrodynamic and morphological process of the river was simulated by applying the Delft3D-Flow module. The domains for the flow model are imported from the RGFGRID and QUICKIN modules of Delft3D. To ensure accurate and stable simulation of the flow (including the secondary flow) and sediment transport a valid simulation time step is selected depending on the Courant (Friedrichs-Lewy) number (CFL) which is defined by:

$$CFL = \frac{\Delta t\sqrt{gh}}{\Delta x \Delta y} \tag{2.3}$$

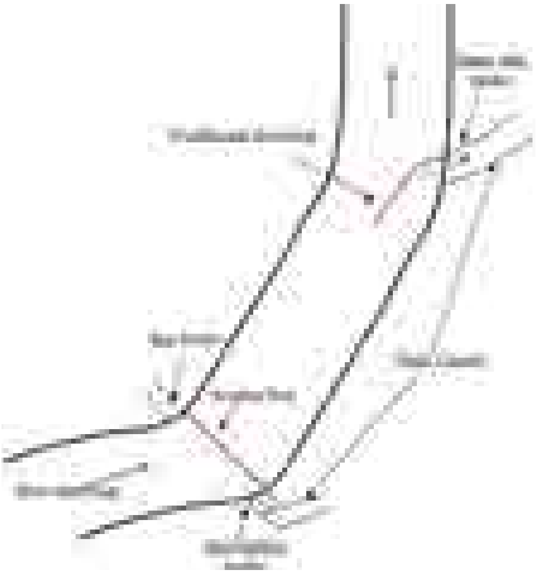
Where, Δt is the time step (in seconds), g is acceleration of gravity, H is total water depth, and Δx or Δy is the minimum value of the grid spacing in either direction (Hydraulics, 2011). To ensure stable model simulation, different time steps were selected for the simulations of different flood levels. All the simulation time steps were selected based on the recommendation stated on the delft 3D - flow manual.

The upstream and downstream cross sections of the river and the intakes are defined as open boundaries in the model. A time series flow data derived from the flow hydrograph was used as flow condition for the upstream boundary. The Bathurst discharge formula was employed to calculate the discharge at different depths so as to generate the stage-discharge relation which was used as flow condition for river downstream boundary and the intakes. Having the riverbed material grading results, the sediment concentration was calculated by the Meyer-Peter-Muller sediment transport formula and then utilized for the upstream and downstream boundary transport conditions.

The default Van Rijn sediment transport formula in Delft3D is not applicable for this research as the size of riverbed material shows great variation and the mean sediment diameter is out of the validity range of the formula. Meyer-Peter-Muller formula was tested through extensive experimental research with uniform and nonuniform sediments and showed good predictions even outside its validity range (Van der Scheer et al. 2002). Thus, Meyer-Peter-Muller formula is selected and used in simulating the sediment transport in the river. The formula was added to the model by preparing a sediment transport formula file (*.tra).

The modern and traditional diversion structures were incorporated in the model as 2D weirs. Since the modern diversion weir is perpendicular to the flow direction, it was represented in the model by one U-weir. The traditional diversion is made of a curved earthen embankment partially along the flow direction and partially across the flow direction with an angle greater than 900 to the flow direction. Hence, it is schematized with a combination of U and V weirs. A file (*.2dw) containing the description about the location and dimensions of the weirs was prepared and used in the model simulation. Figure 5.10 shows the sketch of the diversions layout.

Figure 5.10. Layout of the diversions.



The files prepared for the sediment transport formula (*.tra) and for the local weir (*.2dw) were written in the additional parameters tab in the Delft3D-Flow module so that the model can read and replace the default van Rijn formula with the Meyer-Peter-Muller formula. Similarly, it will enable the model to include the influence of the weirs on the flow simulations.

There were no adequate data for model calibration and validation. However, according to recent research work done on Gash River of Sudan, the model has shown good results when used to simulate flow and sediments for spate flows of different magnitudes (Tsoka 2012; Zenebe 2012). Moreover, a calibration coefficient of 5.7 was used in the sediment transport formula as suggested to give better prediction by Kleinhans and van Rijn (2002) and Ribberink (1998).

2.8. Scenarios

After the schematization and setup of the model, three scenarios were examined in order to figure out the best alternative that could assure optimum floodwater and sediment management in the study area.

Scenario-I

The existing condition maintained is as follows; after the model was run for the existing condition, the problems related to flood management and sedimentation were identified and a set of possible improvement options were clustered in to Scenario-II and Scenario-III.

Scenario-II

Under this scenario four consecutive bed stabilizers at a distance of 180, 330, 430 and 570 meters were introduced upstream of the diversion point in order to fix the riverbed degradation/ erosion which is a source of sediment deposition around the intakes. The bed stabilizers were included in the model as a low weir of height 0.3 m. A guide wall (leaf shaped) of 30 m length was introduced at the center of the stream with the aim of concentrating the flow towards the intakes as well as creating secondary flow currents facilitating sluicing of the coarse bed materials towards the river.

Scenario-III

In this scenario the guide wall upstream of the modern intake is extended by 48 m further upstream and one additional guide wall of length 29 m is added upstream of the traditional intake. The objective of the extended guide wall was to reduce the width of the stream so as to create higher flow velocity and hence sediments could be reduced. The guide wall upstream of the traditional intake is meant for guiding low floods towards the intake enhancing its diversion capacity at low floods.

As the shape of the guide wall has to be defined along the orthogonal grid, it was not possible to put the exact shape of the leaf-shaped guide wall. However, it was attempted to schematize the guide wall resembling leaf-shaped as shown in Figures 5.11a and b.

Figure 5.11a Schematized guide wall.

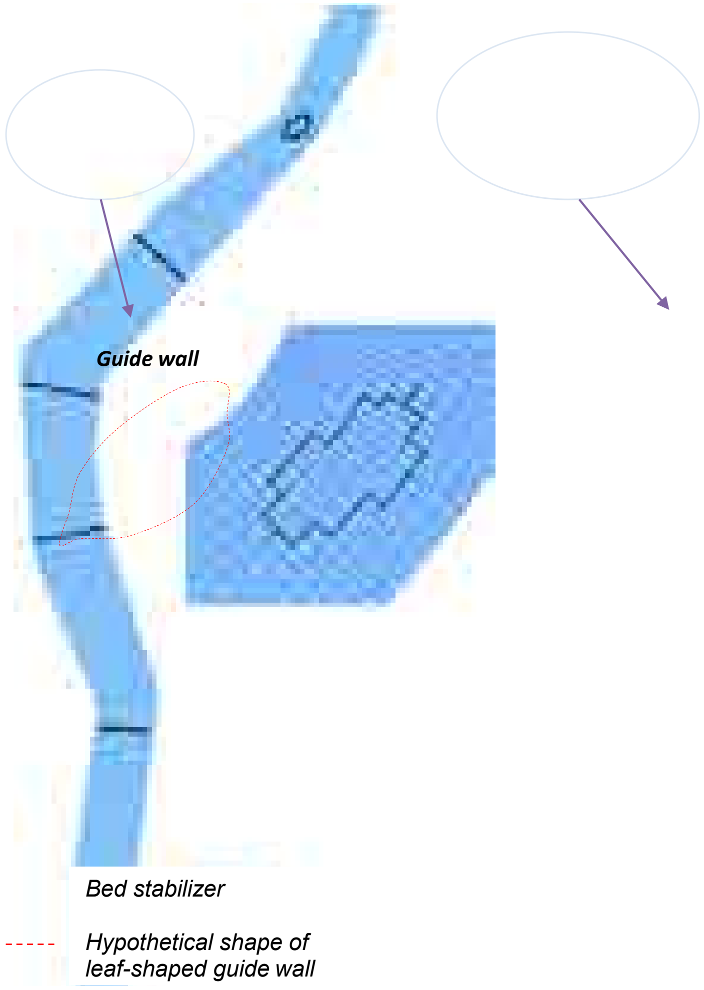
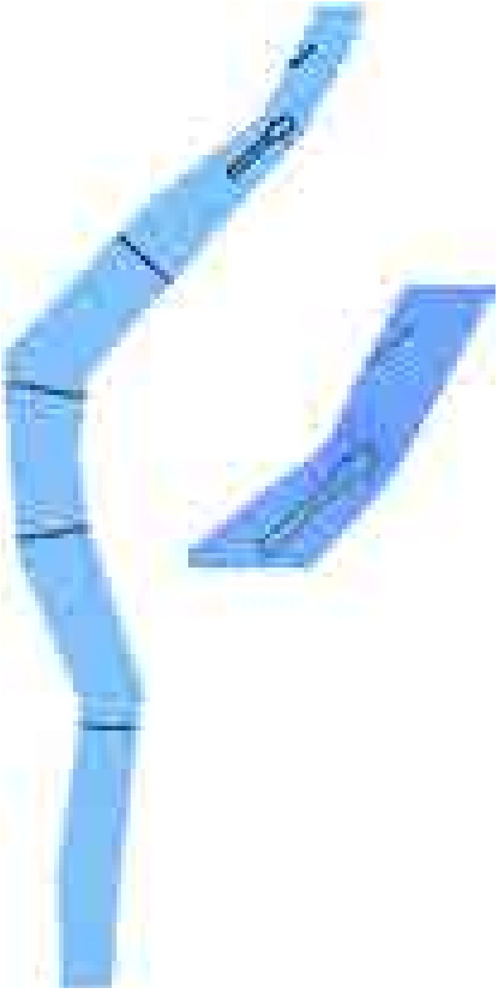


Figure 5.11b. Improvement options under scenario-II (left) and scenario-III (right).

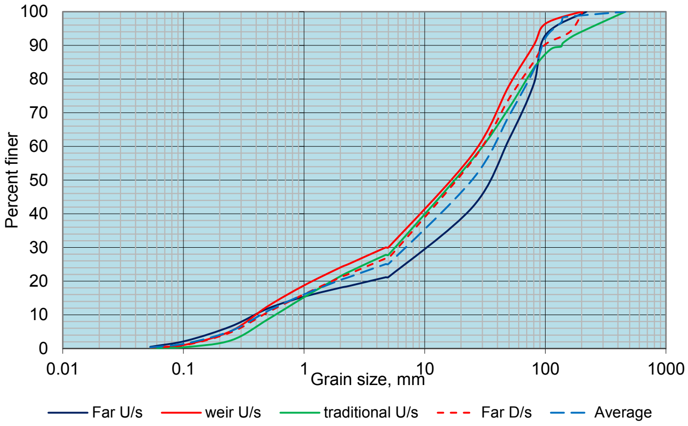


3. Results and Discussion

3.1. Grading Curves

As can be seen from Figure 5.12, the bed-material had sediments of varying sizes with a median diameter ranging from 16.00 to 33.00 mm with an average value of 25.00 mm.

Figure 5.12. Grading curves of sediment from riverbed.



3.2. River Survey

Figure 5.13. Mean cross-sectional area of the river at its most upstream part.

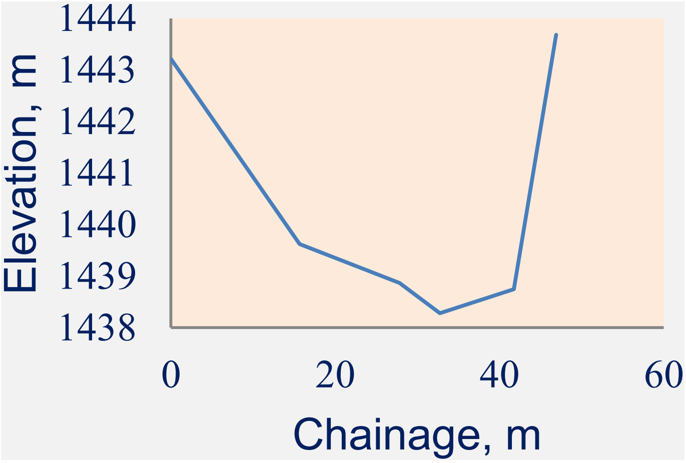
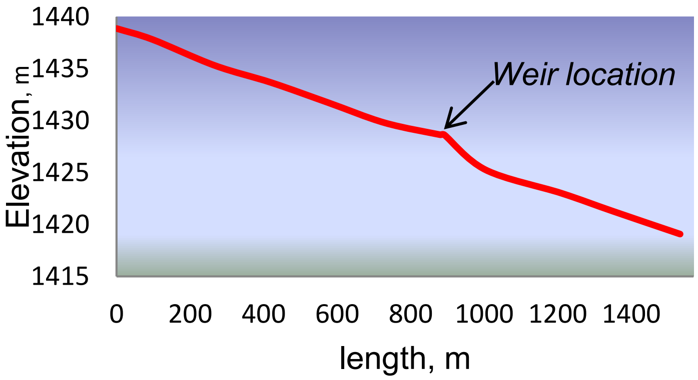


Figure 5.14. River cross section at far upstream (left) and riverbed elevation (right).



Measurement of riverbed elevation made along its length (longitudinal direction) indicated that the slope of the river ranged from 0.011 to 0.015 mm with an average value of 0.012 mm.

3.3. Discharge

Results of the river survey work and sediment analysis and use of equations 2.1 and 2.2 were utilized to estimate the incoming floodwater discharge. Table 5.2 shows discharge computed using Manning and Bathurst equations at upstream and downstream cross sections of the river reach.

Table 5.2. Discharge at upstream and downstream.

Cross section	Flood type	n	A (m2)	P (m)	R (m)	S (m/m)	Q (m3/s) Manning	D84	D*	Q (m3/s) Bathurst
X-1 (Upstream)	High	0.035	91.40	39.90	2.30	0.012	505.80	0.083	12.11	583.30
	Medium	0.035	34.70	30.20	1.20	0.012	121.20	0.083	10.43	135.30
	Low	0.035	10.90	19.10	0.60	0.012	23.70	0.083	8.71	24.90
X-11 (Downstream)	High	0.035	44.70	30.90	1.40	0.012	178.40	0.076	11.18	238.30
	Medium	0.035	19.90	25.00	0.80	0.012	53.30	0.076	9.73	68.50
	Low	0.035	8.80	23.40	0.40	0.012	14.30	0.076	7.89	16.90

3.4. Scenario I: Existing Conditions

3.4.1. Modern diversion

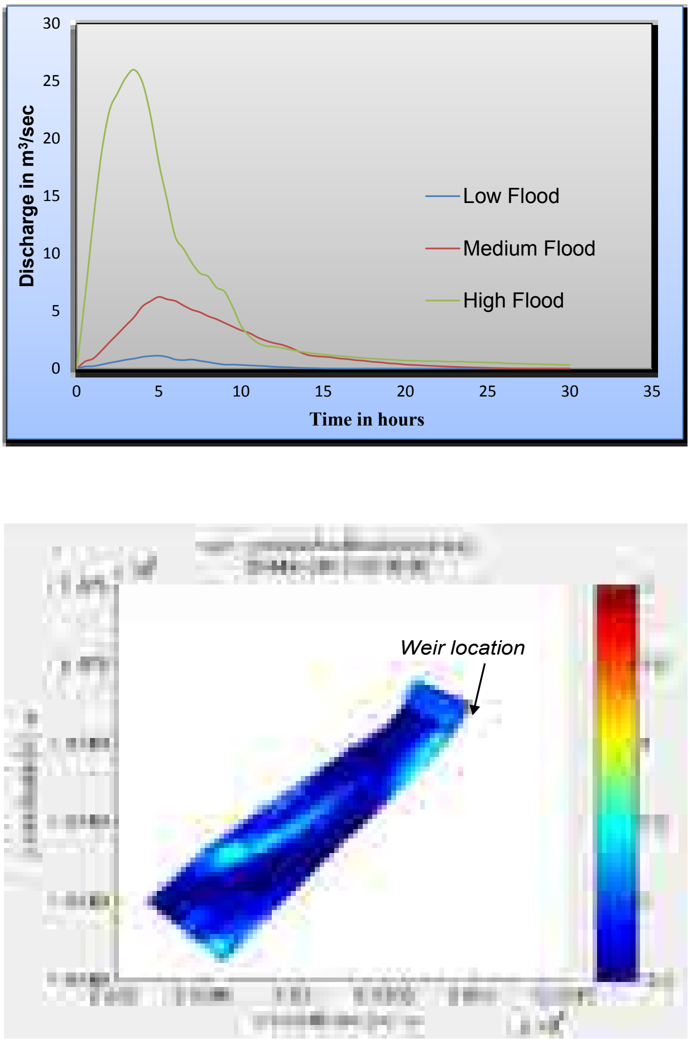
Delft 3D model run to simulate the floodwater levels of the river around the intakes under different flood events (high, medium and low) resulted in the development of the flood hydrograph of the intakes shown in Figure 5.15 (top). Figure 5.15 (bottom) indicates the level of sediment concentration. Table 5.3 shows the comparison of the required abstraction rate at the intakes with the maximum discharge that can be abstracted under the existing condition (Scenario I).

Table 5.3. Floodwater abstraction at intakes.

Flood type	Modern intake, Q req. 16.3 m3/s		Traditional intake) Q req. 12.69 m3/s	
	Max. floodwater depth (m)	Abstraction (m3/s)	Max. floodwater depth (m)	Abstraction (m3/s)
Low	0.34	1.12	0.37	1.75
Medium	0.99	6.23	0.97	23.57
High	2.72	25.49	1.03	26.58

As shown in Table 5.3, the discharge abstraction of the modern intake was considerably lower than the required abstraction rate during medium and low flood events. The maximum floodwater uptake of the intakes is 38.20 and 6.90% of the required abstraction rate during medium and low floods, respectively.

Figure 5.15. Modern intake inflow hydrograph (top) and cumulative erosion/ sedimentation (bottom).

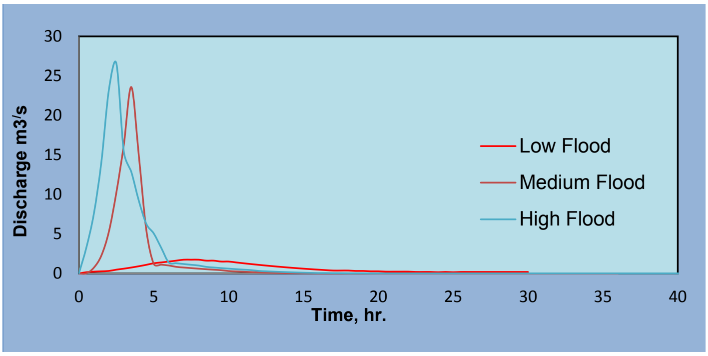


The main reason for the low abstraction rate was the deposition of sediments around the intakes that blocked floodwater flow towards the intakes. This was noted from the morphological simulation results of Delft 3Dn which indicated a possible sediment deposition of 46.00 cm around the intakes. Moreover, the intake was oriented at an angle of 900 with the direction of floodwater in the river, which was not the optimum point of view of floodwater and sediment management. According to the study done by Pirestani et al. (2011), the best intake angle for higher diversion efficiency and minimum sediment entry is from 115 to 1,350. Notwithstanding the lower and medium floods, simulation results indicated higher floodwater levels at the intake during high flood events that enabled the diversion of 25.49 m^3s^{-1} of floodwater as maximum at the intake under the existing modern structure scenario (Scenario I). Nonetheless, as per the model output the maximum abstraction rate indicated above occurred for a short period of time, not more than 10 hours as can be seen from Figure 5.15. The model output further indicated that the total volume of floodwater that could be diverted was 1.16 Mm^3 considering bad season, which could provide 41.00% of the 2.8 Mm^3 water demands of crops in the command area.

3.4.2. Traditional diversion

According to the simulated floodwater level, the maximum water uptake of the traditional intake could be 1.75, 23.57 and 26.58 m^3s^{-1} during low, medium and high floods, respectively (Table 5.3).

Figure 5.16. Traditional intake inflow hydrograph at existing condition.



The intake hydrograph (Figure 5.16) shows a small abstraction rate with a longer period of time at lower floods and high abstraction rates for short duration at medium and high floods. It must be noted that the abstraction time in general is half of the time available with the modern (5 hours) intakes. This was due to the very fact that the traditional diversion structures, which were made of earth/stone/brushwood, etc., collapsed shortly after the onset of high floodwater that generated an excessive amount of dynamic force beyond the capacity that the structure could withstand. This led to the loss of subsequent floodwater that could have been diverted to the main canals. The failure of traditional diversion structures at medium and higher floodwater was common in other countries where spate irrigation is practiced. In Eritrea, traditional diversion structures face minor and major damage as a result of large floodwater of 50 - 100 m^3s^{-1} while complete destruction is imminent at 100 m^3s^{-1} flood (Mehari, 2007). As shown in Figure 14, diversion of floodwater considerably reduced and tended to ease after 5 hours even if there was floodwater in the river. This implied that there was a very short period of time to divert floodwater and, hence, the cumulative volume of floodwater applied to the field was very small.

3.4.3. Performance of the schemes to irrigate their command area

As indicated in sub-sections 3.4.1 and 3.4.2, the diversion capacities of the intakes were very much below the desired ones. However, it was found necessary to do further analysis to quantify the total volume of water diverted and the area that could be irrigated so that the performance of the scheme could be assessed. With the volume of floodwater that could be diverted under any one of three anticipated years/seasons (good, average and bad), the command area which could be fully irrigated was estimated and given in Table 5.4.

Table 5.4. Command area under the existing condition (Scenario I).

Intake	Year/Season	Total volume diverted (Mm^3)	Area irrigated (ha)	Percentage of area irrigated
Modern (Command area 176 ha)	Good	6.63	414.68	236.00
	Medium	2.10	131.49	75.00
	Bad	1.16	72.66	41.00
Traditional (Command area 137 ha)	Good	4.41	275.6	201.00
	Medium	1.52	95.00	69.00
	Bad	0.51	32.00	23.00

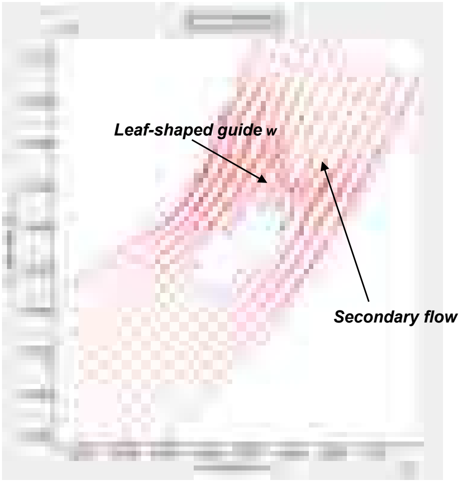
It is obvious that in the good season the diverted flood can easily satisfy the crop water demand of the command area. However, during average seasons it is possible to irrigate 75 and 69% of the command areas of the modern and traditional intakes, respectively. The model estimated that during the bad year/season, characterized with only two large floods, 72.66 and 32.00 ha could be irrigated using the modern and traditional intakes, respectively. These values could be lower as there is no irrigation rotation which allows utilization of all floodwater diverted at the intakes.

3.5. Scenario II: Reinforcement, Guide wall and Bed Stabilizer Intervention

In this scenario, three possible improvement options were examined to assess the effect of improvements on floodwater intakes and sedimentation: a leaf-shaped guiding wall upstream of the modern weir, four consecutive riverbed stabilizers and reinforcement of the traditional intake.

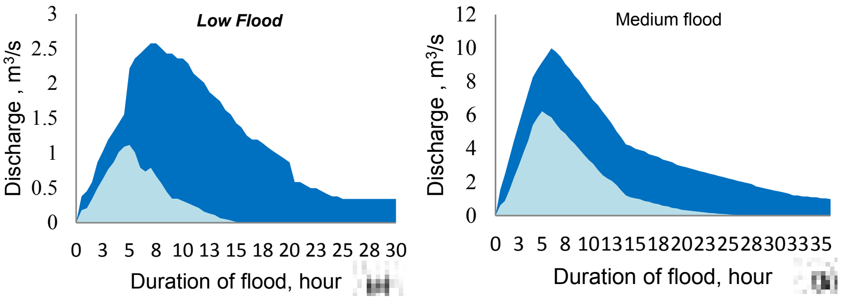
Figure 5.17 shows a leaf-shaped guide wall located at the center of the river to assure floodwater flows into both intakes situated on the left and right sides of the weir. The shape of the guide wall was to create an inner bend so that the entry of coarse sediments could be minimized due to the effect of secondary flow currents.

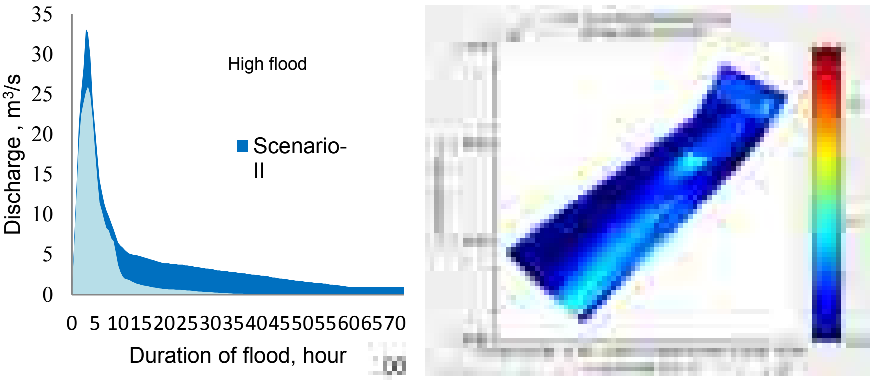
Figure 5.17. Effect of the leaf-shaped guide wall on flood flow pattern.



As can be seen from Figure 5.17 above, the floodwater flow is concentrated at the sides of the river thus raising the water levels at the intakes. As a result, simulated increments of floodwater level of 22, 38 and 58 cm were noted considering low, medium and high floods, respectively. The corresponding simulated hydrographs are shown in Figure 5.18. As can be seen from the figure below, the effect of the intervention was more pronounced in improving the floodwater uptake at low and medium floods than at high flood (see areas colored deep and light blue). Hence, this clearly indicates that the introduction of a leaf-shaped guiding wall upstream of the modern weir and consecutive riverbed stabilizers would only increase the cost of construction and maintenance if floodwater flow is expected to be high or under a good year/season situation.

Figure 5.18. Intake hydrographs of modern structure under Scenarios II (a and b) and Scenarios I and II (c) and cumulative erosion/sedimentation under Scenario II (d)

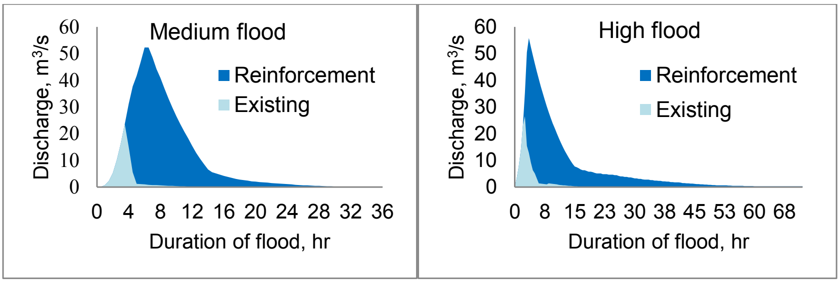




It must be noted that the increment in the level of floodwater at the intakes is the result not only of the guiding wall but of the bed stabilizers that minimized the sediment deposition around the intake by taking steps to stop erosion of the upstream riverbed that minimized the amount of sediments reaching the diversion.

The enforcement of the traditional intake on the existing structure, in such way that it could withstand the impact of increased dynamic force of floodwater, brought about a significant increase in the volume of floodwater diverted as the intake was capacitated to abstract for a longer period of time with no damage. The reinforcement resulted in strengthening the existing diversion which was in the range of 0.6 to 1.0 m in height, top width being about 1.00 m and the bottom width to be fixed after checking slope stability of the canal. The design of the diversion could be modified in order to make it capable of withstanding the impact of the force of floodwater at the discharge level of 238 m^3s^{-1}, which was the estimated discharge at the downstream of the traditional diversion. However, it should be noted that the increased height could cause diversion of more floodwater that can damage the canals and command area; the height increment must be made with most care. Figure 5.19 shows the change in shape of the traditional intake inflow hydrograph at medium and high floodwater flow situations.

Figure 5.19. Intake hydrograph of reinforced traditional structure.



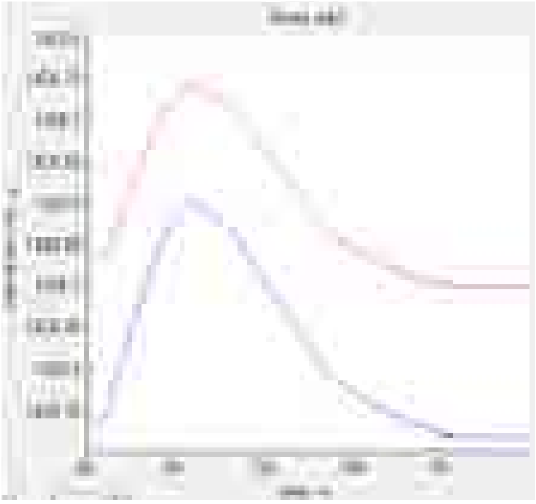
The simulated volume of floodwater made available as a result of reinforcement was large, and the scheme could irrigate all the command area even during the bad season. The simulated improvements made on the structures, both traditional and modern ones, improved the level of floodwater that could be diverted to the farms.

Nonetheless, it must be noted that change in the schemes may have negative implications on the existing traditional water use and share regulations and rule; people tend to cultivate more as a result of increased floodwater availability in the area.

Simulation under Scenario II indicated that the set of interventions sought would reduce the level of floodwater by 15 cm (see Figure 5.20) at the intake located downstream of the traditional intake. This would imbalance in floodwater sharing between upstream and downstream users and may lead to a conflict over the meager water resource, in the area. However, this reduction in floodwater level was not because most of the floodwater was diverted at the modern intake, rather it appeared the floodwater would be flowing far away from the intake during low floods.

Sediment depositions were observed in front of the leaf-shaped guide wall, even after interventions under Scenario II, which could affect the flow pattern in the river and block the flow of consecutive floods to the intakes.

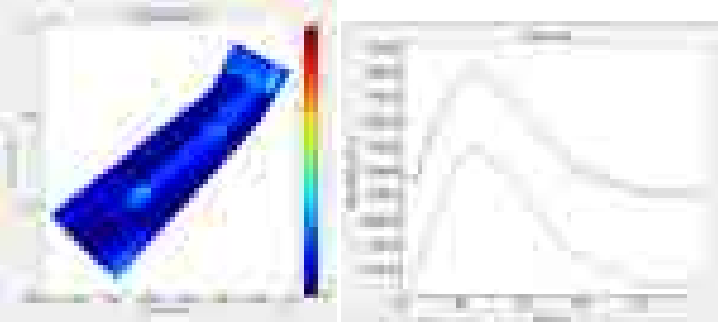
Figure 5.20. Upstream and downstream floodwater level at the intake under the existing traditional structure (red) and under Scenario II (blue)



3.6. Scenario III: Extending the Leaf-Shaped Guide Wall and Introducing Another Guide Wall Upstream of the Traditional Intake

To overcome the drawbacks of scenario-II, the leaf-shaped guide wall was extended by 48 m further upstream and one additional guide wall of 29 m was introduced upstream of the traditional diversion. The model simulation showed that the sediment deposition was reduced as can be seen from Figure 5.21; the fact that the depth of sediment is almost zero everywhere, guaranteed the desired pattern of floodwater flows.

Figure 5.21. Sediment deposition after scenario III (right) and floodwater level at the intake of the existing structure (red), Scenario II (blue) and Scenario III (green)



Similarly, the provision of a guiding wall upstream of the traditional intake adequately minimized the decline in floodwater level observed under scenario II. As shown in Figure 5.21, the floodwater level in the traditional intake is brought to a level which is slightly higher than the existing condition during the low floods. As a result, the desired floodwater abstraction rate was obtained and the sediment deposition around the intakes alleviated. However, it does not necessarily mean that the scheme is capable of supplying enough floodwater to meet the water requirement of the crops in the command area. Hence, the effect of the interventions was analyzed by comparing the area being irrigated under existing conditions with the area that could be irrigated after the intervention.

Under the average flood year/season, applying scenario II and scenario III could enable the scheme to fully irrigate all the command areas without any moisture stress. However, during the bad year/season, full irrigation is possible for 84 and 95% of the command areas through the improvement options defined as scenario II and scenario III, respectively (Table 5.5).

Table 5.5. Command area under the existing condition (Scenario I).

Scenario	Year/ Season	Total volume diverted (Mm^3)	Total area irrigated (ha)	Percent area that can be irrigated
I	Good	6.63	414.68	236.00
	Average	2.10	131.49	75.00
	Bad	1.16	72.22	41.00
II	Good	16.24	1,015.28	577.00
	Average	5.38	335.97	191.00
	Bad	2.36	147.75	84.00
III	Good	18.57	1,160.80	660.00
	Average	6.23	389.67	221.00
	Bad	2.67	167.09	95.00

4. Conclusion and Recommendation

The following major conclusions and recommendations are drawn from the study with regard to optimization of flood and sediment management in Aba'ala spate irrigation.

4.1. Conclusions

- Higher sediment deposition of up to 46 cm around the modern intakes made the abstraction rate to be limited to 7 and 38% of the required 16.3 m^3s^{-1} at lower and medium flood events. Likewise, the traditional intake diverted 14% of the required 12.69 m^3s^{-1} abstraction rate at lower flood events.
- At higher flood, the modern intake is capable of diverting at a rate of 25.5 m^3s^{-1}. However, diverting flood equal to or greater than the required 16.3 m^3s^{-1} was possible for short durations (4 hours) due to the fast rising and fast declining nature of the incoming floods.
- A higher abstraction rate of 23.6 and 26.6 m^3s^{-1} was observed in the traditional intake during medium flood and high flood, respectively. However, diverting at higher rates is shortly halted after 6 hours due to collapse of the diversion as a result of the impact of force of floods.
- In an average flood season, the modern intake can divert 75% of the required 2.8 Mm^3 of floodwater while the traditional intake diverts 69% of the required 2.2 Mm^3 of floodwater. In a bad flood season, the percentage is declined to 31% in the modern intake and to 25% in the traditional intake.
- Reinforcing the traditional intake (leaf-shaped guiding wall and bed stabilizers) resulted in a better flood and sediment management practice by reducing sediment deposition to almost zero around intakes. However, this failed to ensure equitable sharing between upstream and downstream intakes as a water level decline of 15 cm was seen in the traditional intake at low flood levels.
- Putting up a 78 m long guide wall upstream of the modern intake and bed stabilizers together with a 29 m long guide wall upstream of the traditional intake gives good results in terms of improving diversion capacity of both the intakes and assuring a fair share of water between upstream and downstream intakes.
- The command areas under both intakes can be expanded by 100% if the interventions listed under scenario III (extended guide walls upstream of modern intake, bed stabilizers, guide wall upstream of traditional intake and reinforcing traditional intake) are applied.

4.2. Recommendation

- For better floodwater uptake, reduced sedimentation and fair share of floodwater, the modern intake should be equipped with the extended guide wall and bed stabilizers with a guide wall upstream of the traditional intake.
- As the bed stabilizers can raise the water level, it is recommended to build multiple intakes at the section of the river rehabilitated with bed stabilizers so as to increase the overall diversion efficiency.
- Some modification of width and side slope should be done to ensure stability and strength of traditional intakes. However, the height must be kept as fixed traditionally (0.6 - 1.0 m) to control damage of command area as a result of higher flood diversion.
- Regular inspection after every flood is recommended for any sediment deposits upstream of the extended guide wall.

- Simulations were done based on a single flood event. For future research, it is recommended to study the hydrograph for at least one season and test the seasonal floodwater flow and sediment deposition patterns.
- Further research needs to be done to verify the inputs, flood discharges and sediment concentration used in this research. It is also recommended to calibrate the model before using the results for any decision making.
- Design of diversion structures must be based on the fundamental principles and construction done by qualified contractors.

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