Journal of Hydrology: Regional Studies 53 (2024) 101816

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh

# Hydrodynamic modelling to develop design and operational options for sedimentation reduction in irrigation schemes, Ethiopia

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ARTICLE INFO

*Keywords:*
Irrigation
Sediment transport
Design modification
Operational changes
Soil erosion

ABSTRACT

*Study region:* The Great Rift Valley Basin of Ethiopia, Arata-Chufa (100 ha) and Ketar (430 ha) irrigation schemes.

*Study focus:* Sedimentation triggers malfunctioning in irrigated agriculture by decreasing canal discharge capacity and increasing operation and maintenance costs. The current study coupled a hydrodynamic sediment model with the output of an erosion model to analyse sedimentation problems, employing data on discharges, water levels, sediment load, and sediment concentration collected over two years (September 2017 to September 2018). The effects of design (canal lining, building a settling basin, and changing longitudinal bed slope) and operational (sediment flushing) modifications on sediment reduction were simulated with the Hydrologic Engineering Center's (HEC) River Analysis System (HEC-RAS) model.

*New hydrological insights for the region:* The model simulation indicates that the most promising low-cost option to reduce sedimentation is flushing during the rainy season, reducing deposition by 82% (Arata-Chufa) and 57% (Ketar). The second option is lining the canal, particularly for a scheme mainly experiencing river sediment like Arata-Chufa, where deposition would be reduced by 28%. Construction of a new settling basin with a flushing option would reduce deposition by 63% (Arata-Chufa) and 42% (Ketar). Changing the bed slope of the severely silted canal section has little effect on sediment reduction. Therefore, operational changes are more promising low-cost options than design modification to reduce sediment deposition in SSI schemes.

## 1. Introduction

Irrigated systems can easily be hampered from functioning efficiently by sedimentation problems. Excessive sediment triggers the malfunctioning of irrigation schemes by clogging infrastructures and causing aggradation and degradation of canal beds (de Sousa

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https://doi.org/10.1016/j.ejrh.2024.101816
Received 30 June 2022; Received in revised form 3 May 2024; Accepted 5 May 2024
Available online 17 May 2024

et al., 2021; Grancharova and Patamanska, 2018), which exerts a considerable decrease in canal transport capacity (Ahmed et al., 2018; Akkuzu et al., 2008; Salmasi et al., 2023). Belaud and Baume (2002) claim that excessive sediment deposition can account for 40% of canal discharge reduction. These sedimentation problems incur high operational and maintenance costs (O&M) (Belaud and Baume, 2002; Depeweg and Mendez, 2002; Depeweg et al., 2016), and the severity of such problems increases for irrigation schemes with limited O&M budget (Lawrence and Atkinson, 1998). In addition, the location of the schemes is associated with the severity of the problem. For instance, in regions of sub-Saharan Africa (SSA) where land degradation is especially dire (Berihun et al., 2022), irrigation schemes exhibit severe sedimentation problems. The irrigation schemes in these regions are often vulnerable to river and overland flow sediment courses. While sedimentation in irrigation schemes ultimately comes from soil erosion, the severity of the problem is aggravated by design and O&M challenges (Gurmu et al., 2019).

Taking sediment into account in canal design is challenging because theories and models of sediment transport behaviour are based on river conditions which differ from man-made canal conditions. It is often assumed that uniform and steady-state flow conditions exist and that sediment transport is in a state of equilibrium (Depeweg and Mendez, 2002; Nestor, 1998). The underlying concepts of sediment transport, such as the development of bedforms and friction factors that are crucial for designing a regime canal, were developed for the conditions that specifically prevail in a natural stream, but these are quite different from conditions in man-made irrigation canals (Depeweg and Mendez, 2002; Munir, 2011; Osman, 2015). Under unsteady state conditions, when there is a large change in the incoming discharge and sediment, the available methods for designing regime canals are inadequate (Depeweg and Mendez, 2002; Depeweg and Méndez, 2007). The quantity of incoming sediment varies not only with time but also with the location and sediment grain size. In particular, the performance of irrigation schemes designed with a longer feeder canal deteriorate when encountered overland sediment inflow at multiple locations with varying sediment conditions.

When sedimentation reduction is aimed, irrigation canal design can minimize the cost of sediment management by transporting the sediment to field plots or a specific location for removal at the lowest cost (Belaud and Baume, 2002; Belaud and Paquier, 2001; Depeweg and Mendez, 2002; Lawrence and Atkinson, 1998). Nonetheless, desilting costs are excessive (Mahessar et al., 2020), and the rate of sediment deposition often demands a higher frequency of desilting than what can be financed with allocated funds (Lawrence and Atkinson, 1998). Over 60% of the annual O&M costs may spent on dredging river sediment influx (Osman et al., 2019). In some schemes, overland flow contributes a considerable quantity of sediment, particularly in gravity irrigation schemes with a long feeder (headrace) canal, and neglect of overland flow in design and O&M has worsened sedimentation problems, requiring farmers to expend a great amount of labour on desilting (Gurmu et al., 2019). Irrigation canals are designed to cope with sediment from a river course. However, sediment influx from an overland flow can considerably alter the hydrodynamics of sediment transport (Assaye et al., 2021), which partly emerges from the expansion of irrigated agriculture (Taye et al., 2021).

Previous studies have investigated the role of design and O&M change in reducing sedimentation problems (Belaud and Baume, 2002; Depeweg et al., 2016; Munir, 2011; Nestor, 1998; Osman et al., 2017; Osman, 2015; Paudel, 2010; Theol et al., 2019). For example, the study by Ali et al. (2021) investigated the role of the design approach on sedimentation problems using the Hydrologic Engineering Center's (HEC) River Analysis System (HEC-RAS) model. Another study by Ochiere et al. (2015) using similar HEC-RAS model simulated an underground irrigation canal to uncover the causes of canal capacity reduction. Two other similar studies by Osman et al. (2017) and Theol et al. (2019) investigated the role of scheme operation during peak flood season in reducing sedimentation. Theol et al. (2020) investigated the effect of gate opening on sediment deposition in an irrigation canal and reported that opening the gates near the off-taking canal resulted in less sediment deposition in the branch canal as compared with opening the gates at the farthest point. Many other studies often focused on analyzing the performance of a settling basin in reducing sediment deposition in an irrigation canal. Namu (2017) compared the effects of continuous and periodic flushing of a settling basin on sediment deposition and found that a settling basin with a continuous flushing option is superior to those without flushing systems, with over 65% efficiency. Chemeda and Dinka (2020) analyzed the effect of different frequencies of flushing settling basins and concluded that more frequent flushing improves the settling basin performance. A similar study by Salmasi et al. (2023) evaluated the effect of various design approaches on the performance of a settling basin and showed that the United States Bureau of Reclamation approach yielded high efficiency. Bhatti et al. (2021) investigated the role of a hypothetical setting basin on sedimentation reduction in an irrigation canal and reported that about a 16% reduction in sediment deposition can be achieved. de Sousa et al. (2022) examined the driving factors of bathymetry changes in an irrigation scheme and underscored that a significant change in slope over time due to morphological changes caused sediment deposition in the Chokwe irrigation scheme in Mozambique.

These studies focused on reducing river sediment influx and deposition in irrigation canal by improving design and operation options. However, some schemes are hampered by in-situ sediment influx from surface erosion after the intake structure, and overlooking the overland sediment inflow and only focusing on river sediment influx barely allows for sustainable sediment reduction. The current study investigated sediment-reducing options in small-scale irrigation (SSI) schemes suffering from both river and overland flow sediment. Specifically, this study coupled a river model with the output of an erosion model to explore the effects of design and operational modifications on sediment reduction for a combined river and overland sediment influx. Accounting for both overland and river sediment influx is the viable option for sustainable sediment deposition reduction in an irrigation scheme.

## 2. Materials and methods

### 2.1. The study area

The current study focused on two SSI schemes in Ethiopia (Fig. 1) with severe sedimentation problems originating from different sources of sediment influx. They are typical cases of irrigation schemes in Ethiopia that suffer from severe sedimentation problems.

These were the Arata-Chufa SSI scheme (7° 59’ N and 39° 02’ E, 100 ha), affected by sediment that mainly comes from river sources, and the Ketar medium-scale irrigation scheme (7° 49’ N and 39° 02’ E, 430 ha), which suffers from a combination of sediment from overland flow and river (Gurmu et al., 2022).

The Arata-Chufa has two main canals with a total length of 1.3 km and supplies water to ten irrigation blocks (Table 1 and Fig. 2a). The scheme has eight 3712 m long secondary canals. The Ketar scheme was constructed in three sections (Ketar 1, Ketar 2 and Ketar 3) with a single main canal of 12.2 km. Although the Ketar is a medium-scale (irrigation scheme with a command area between 200 and 3000 ha) irrigation scheme, the current study focused on Ketar 1, a small-scale scheme with 120 ha and some 7 km from the intake, where severe sedimentation problems exist (Fig. 2b). In this study, the term “small-scale” is used when referring to “Ketar 1” and “medium-scale” is used when referring to the “Ketar 1, 2, and 3 schemes combined”. The Ketar scheme is designed with a long headrace canal to compensate for the slope differences between the command area and intake location.

Note that the layout of the two schemes was drawn with different horizontal scales.

### 2.2. Methodology

The current study developed and simulated design and operational options for reducing sedimentation problems in SSI schemes. The study used the HEC-RAS hydrodynamic sediment model to simulate the sediment transport behaviour of an irrigation canal in response to design and operation modification (Fig. 3). Mathematical sediment models are useful tools that offer greater room for flexibility to analyse various scenarios, although they are subjected to uncertainties. The following approaches and tools were used to acquire data for the sediment model and analyse options for reducing sedimentation:

- A participatory monitoring programme: the participatory monitoring programme was conducted for two years, from 2017 to 2018, to collect data on discharge, water level, sediment, topographic survey, and canal characteristics. These data were used to calibrate the validity of the HEC-RAS model and to analyse the role of design and operation modifications in reducing sedimentation. For details on the monitoring programme and data analysis, see Gurmu et al. (2022).

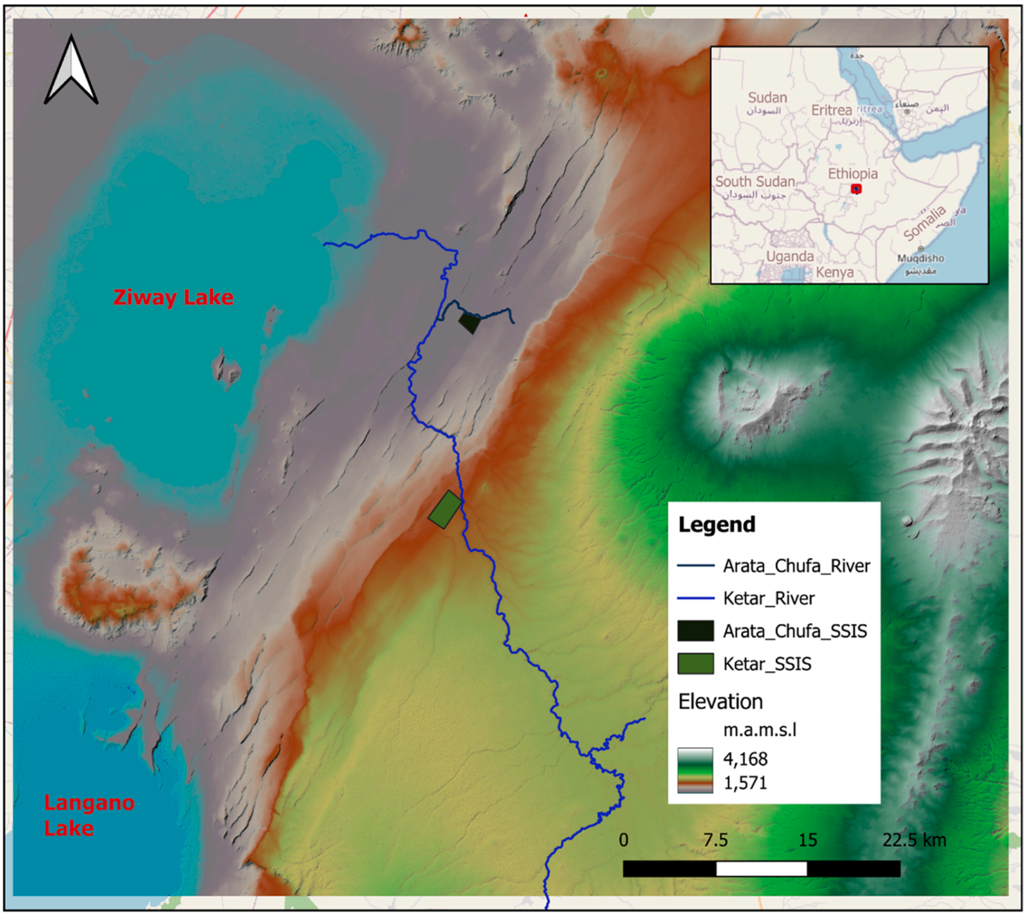


**Fig. 1.** Location map of the study areas: Arata-Chufa small-scale and Ketar medium-scale irrigation schemes.

**Table 1**
Characteristic of the study area: Arata-Chufa small-scale and Ketar medium-scale irrigation schemes (Gurmu et al., 2019, 2021, 2022).

| Scheme characteristics | Arata-Chufa | Ketar |
|---|---|---|
| Command area | 100 ha | 430 ha |
| Number of beneficiaries | 324 | 1087 |
| Number of main canals | 2 | 1 |
| Canal geometry | Rectangular, trapezoidal | Rectangular, trapezoidal, irregular |
| Feeder canal length | 600 m | Some 5000 m |
| Average bed slope of FC | 0.16% | 0.37% |
| Sediment sources | Mainly river | River and overland flow |
| Canal lining (concrete) of the hotspot section | Mostly lined | Partly lined |
| Sedimentation challenge | Moderate | Severe |
| River sediment inflow (measured) | 220 $m^3$ | 1741 $m^3$ |
| Overland sediment inflow | 8 $m^3$ | 2042 $m^3$ |
| Desilting campaign | Mostly annual | Sometimes biannual |
| Desilting output | 0.21 $m^3$/day | 0.81 $m^3$/day |
| Gated offtakes | Broken/non-functional | Semi-functional |
| Operated by | WUA/farmers | WUA/farmers |

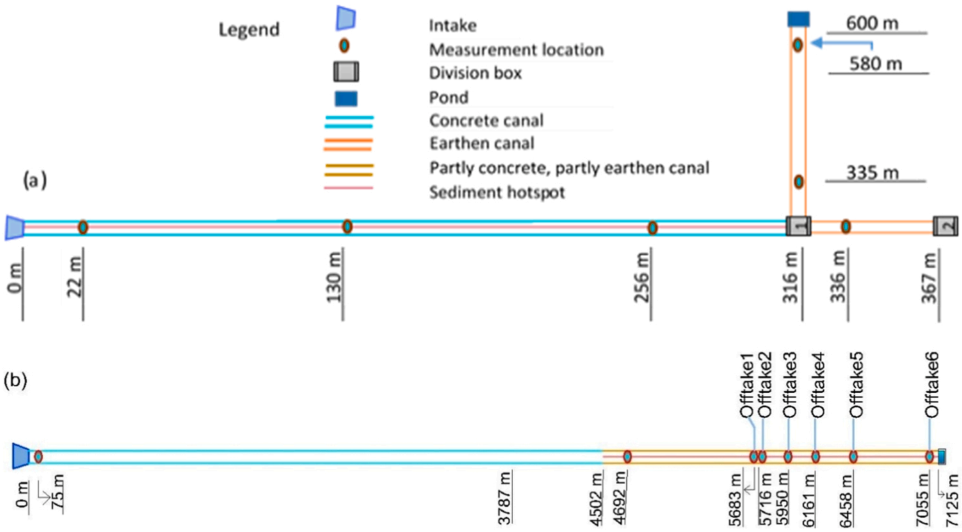


**Fig. 2.** Layout of small-scale Arata-Chufa (a) and medium-scale Ketar (b) irrigation schemes.

- Modelling overland flow sediment yield: the revised universal soil erosion equation (RUSLE) model was used to model overland sediment inflow into the schemes, which was later used as boundary conditions for calibration and analysis in the sediment model. The overland sediment inflow computed by the RUSLE model is considered in the HEC-RAS model as a point source influx. The overland sediment is added to the HEC-RAS model as a boundary condition data of later influx. For details on RUSLE modelling, see Gurmu et al. (2021).
- A hydrodynamic sediment model: the hydrodynamic Hydrologic Engineering Centre's (HEC) River Analysis System (HEC-RAS) 6.0 model (HEC, 2022b) was used to analyse the effect of canal design and operation modification on sedimentation.

### 2.3. Sediment modelling

Two models are required to model the sediment transport in irrigation canals, the flow model for solving hydraulic parameters and sediment transport, and the morphological model for solving sediment mixing and transport (Paudel, 2010). There are numerous mathematical models available for open channel simulation, but only a few of the models have sediment transport modules (Munir, 2011; Nestor, 1998). In accordance with the spatial dimension and orientation of the parameters used for defining sediment and water movement, these models are classified as 1D, 2D horizontal and vertical models, and quasi-3D models. The prediction of these models using the same input data vary significantly (Nestor, 1998). The applicability of these models depends on the conditions, and the three-dimensional models (3D) are mostly applied to study complex flow and sediment transport in large water resources systems (Munir, 2011). These models follow either a depth-integrated or a three-dimensional approach (Munir, 2011). The two-dimensional vertical (2DV) and two-dimensional horizontal (2DH) models can be applied to irrigation canals, and can be used to predict transport rates in natural water resources. 2DH models are based on the depth-integrated equation of motion- and depth-integrated sediment

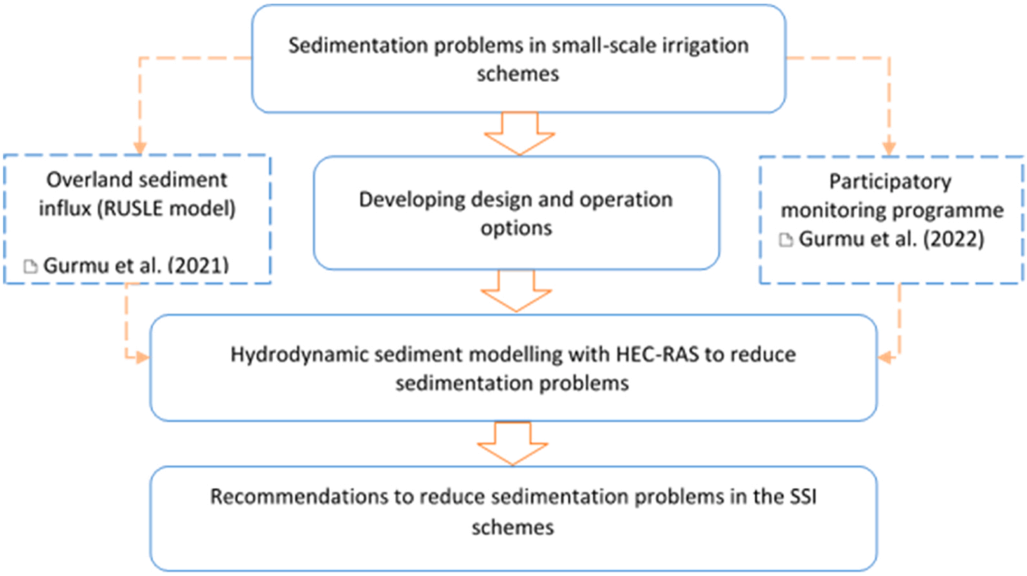


**Fig. 3.** Methodological framework used to investigate the effect of design and operation modification on sediment transport in irrigation canals.

transport model (Paudel, 2010). 1D models are widely used to simulate a long-term morphological change in non-wide irrigation canals (Munir, 2011; Paudel, 2010). Irrigation canals are usually considered non-wide when the bed width-to-water depth ratio (B-h) is less than eight (B-h$<$ 8) (Nestor, 1998).

Haghiabi and Zaredehdasht (2012), as cited by Mohammad et al. (2016), compared one-dimensional models and claimed that the HEC-RAS model is superior in forecasting the details of cross-sectional outputs for rivers. The HEC-RAS model has been deployed to irrigation canals for various applications: to evaluate the sensitivity of offtake discharges to the inflow discharge at the intake (Shahrokhnia and Javan, 2005); to analyse the effect of change in Manning roughness on offtake discharges (Shahrokhnia and Javan, 2007); to analyse the management and operation of irrigation canals (Kamran et al., 2021; Clarke et al., 2010); to analyse the performance of sand-trap structure (Adhi and Ontowirjo, 2021); and to analyse the effect of different canal design approaches on sediment transport (Ali et al., 2021).

The HEC-RAS model is one of several widely used public domain sediment models that offer a range of functionalities. It can be used for computing 1D steady water surface profile, 1D and 2D unsteady flow computations, mobile bed sediment transport, and water temperature/quality modelling (HEC, 2022a). The steady water surface profile computational procedure is based on the solution of the energy equation. The unsteady flow water surface profile is computed based on the continuity and the momentum equation. The model uses the energy equation for gradually varied flow and the momentum equation for rapidly varied flow conditions, when there is a transition from subcritical to supercritical flow and/or supercritical to subcritical flow. The sediment transport potential is computed by grain size fraction from hydraulic simulation of sorting and armoring (HEC, 2022b). In this study, the open-source 1D HEC-RAS 6.0 (https://www.hec.usace.army.mil/software/hec-ras/) model was used to analyse the effect of canal design parameters modification and changes in operational practices on sediment reduction in SSI schemes.

### *2.4. Description and calibration of the HEC-RAS model*

The 1D quasi-unsteady HEC-RAS model computes the water surface profile by solving the continuity and momentum equation expressed in the form of a partial differential equation. The sediment transport model uses the quasi-unsteady flow series by solving steady flow backwater equations at discrete time intervals. The parameters used for calibration are Manning Roughness (1D hydraulic model) and transport function, sorting and armoring, and fall velocity method (1D sediment model).

To calibrate the HEC-RAS model, data on discharges, water level, sediment loads and sediment concentration was collected over a two-year period from September 2017 to September 2018 in both the Arata-Chufa and Ketar schemes (Gurmu et al., 2022). The model was calibrated in two steps: 1) calibration of the 1D quasi-unsteady hydraulic model, followed by 2) 1D sediment model calibration. In step 1, measurements of discharges and water levels were used to establish a representative Manning roughness coefficient for the hydraulic model. In step 2, measured sediment data (river inflows, particles grading) and estimated overland sediment inflow were used to choose a suitable transport function, sorting and armoring, and fall velocity methods that yield accurate prediction of sediment load in the canal compared with other methods. Overland sediment inflow was added to the model as a boundary condition by choosing a location downstream of major gullies which discharged surface runoff into the main canal. The overland sediment inflow was modelled using the RUSLE model, an empirical erosion model recognized as a standard method to calculate the average risk of erosion (Gurmu et al., 2021). The surface runoff boundary condition for overland sediment inflow is computed by the Rational method. The sediment load computed by the model was compared with the measured sediment load to calibrate the sediment model.

Cross-section measurement was performed before and after sediment was cleaned from the canal. The calibration period was from September 2017 to May 2018, while the model was validated from January 2017 to May 2017.

Average monthly flow series (water levels and discharges) and sediment influx were used for calibration and validation, see Gurmu et al. (2021). For scenarios during the irrigation season, concrete lining of the main canal, construction of a settling basin and raising the canal bed, a sediment rating curve was developed from the measured river sediment influx for sediment model boundary conditions. The result of the RUSLE model (Gurmu et al., 2021), combined with sediment influx during the irrigation season was used to develop a rating curve to analyse the scenario during the off-irrigation season (flushing the sediment). A slight change was made to the Manning roughness to calibrate the sediment model. Various methods are available in the HEC-RAS model for sediment transport capacity, sorting and armoring, and fall velocity for simulating sediment transport in the canal. Engelund-Hansen transport function, Copeland (Ex7) sorting and armoring method, and Rubey fall velocity approaches were used for the comparative advantage of precisely predicting the sediment in the canal over the other approaches.

The hydraulic model performance was evaluated using statistical error indices, water levels and discharges in the main canal. The root mean square error (RMSE), the root mean square error-observations standard deviation ratio (RSR), the percent bias (PBIAS), the *t*-statistics and the Nash-Sutcliffe Efficiency Coefficient (NSEC) were used to evaluate the performance of the HEC-RAS model (Moriasi et al., 2007; Gupta et al., 1999; ASCE, 1993; Nash and Sutcliffe, 1970). The equations for computing performance indices are presented in the supplementary material Appendix C.

### 2.5. Scenarios for reducing sediment deposition

The two schemes experience almost the same types of sediment influx, where nearly 60% of the sediment inflow is sand fraction. For details of sediment types, see Gurmu et al. (2022). The main sources of sediment in the canal system in the two schemes are (i) sediment from the river and (ii) sediment from overland flow. About 794 and 3118 farmer's days were required to dredge the sediment from the Arata-Chufa and Ketar schemes, respectively (Gurmu et al., 2022). Flash floods can occur at any time of year, leading to immediate blockage of the canal. Sediment due to flash floods upstream of the intake was accounted for with irrigation water abstraction. The sediment due to flash floods downstream of the intake is insignificant due to non-concentrated flow, as there is no channel flow. The sediment due to high rainfall intensity was modeled by the RUSLE model based on the rainfall erosivity factor.

Four scenarios of modifying the design or operation to reduce sedimentation were formulated:

- Scenario 1: Concrete lining of the canal
- Scenario 2: Constructing a new settling basin (with or without flushing)
- Scenario 3: Increasing the longitudinal bed slope
- Scenario 4: Sediment flushing during the rainy season

The first three scenarios involve options to modify the design, and the last scenario involves an operational option.

#### 2.5.1. Scenario 1: concrete lining of the canal

The schemes were designed and built with a partly concrete-lined main canal. To reduce sedimentation problems, farmers in both schemes proposed to line the remaining part of the main canals (Gurmu et al., 2019). This scenario simulated the effect of lining (roughness) the remaining alluvial section of the main canal with concrete on reducing sedimentation. About 56% (L = 600 m) and 52% (L= 7125 m) of the main canal, in the Arata-Chufa and Ketar schemes respectively, were lined with concrete (Fig. 2). The sediment hotspot section was lined in the Arata-Chufa (L = 316 m) and was built as an alluvial canal in the Ketar scheme (L = 2433 m). Since implementation of this scenario would incur construction costs, we analysed the possible effect of lining a smaller length of the unlined main canal section, moving from the severe (downstream) section to the moderate (upstream) section. To analyse the effect of lining on sediment deposition, three different Manning roughnesses of concrete finishing were considered, namely smooth concrete finished (n=0.012); average concrete unfinished (n=0.015); and rough concrete unfinished (n=0.018).

#### 2.5.2. Scenario 2: constructing a new settling basin

One common method for increasing canal capacity is to build a settling basin close to the intake where the sediment deposited from the rivers is flushed back into the river. However, there are cases in some schemes where the majority of the sediment comes from overland runoff at multiple locations. In the current study, a settling basin was introduced downstream of the overland sediment inflow location to manage both river and overland flow sediment. Two options were considered in the new settling basin. The first of these involved the option not to flush, but only to store the sediment influx to increase the canal capacity during the irrigation season. This procedure might help to desilt the sediment at the lowest possible cost. As the new settling basin would involve construction costs, its sizing could be optimized by increasing the frequency of the desilting campaigns. The second option is to combine the settling basin with a flushing service during the rainy season.

#### 2.5.3. Scenario 3: increasing longitudinal bed slope

In designing a gravity irrigation scheme, it is challenging to find optimum values of hydraulic and morphological characteristics which avoid the erosion and deposition of sediment, particularly in an irrigation scheme with a longer headrace canal running parallel to a river. Such a scheme is designed with adequate bed slope to compensate for the elevation difference between the headwork and field plots, which is capable of transporting the sediment that comes from both river and overland flow. Usually, the water level in the river is below ground level and the canal is laid with a bed slope relatively less steep than the river bed slope. Hence, the canal has a lower capacity for sediment transport than the river. Laying the canal with a relatively steeper bed slope is costly, as it involves copious groundwork and lining of the canal to avoid channel bed degradation, or requires pumping to elevate the irrigation water above the ground level. Thus, the slope needs to ensure that scouring and sediment deposition are avoided. The irrigation schemes we studied, particularly the Ketar scheme, reflect the above conditions, in which the headrace canal travels some 5 km from the intake to the field plots.

Increasing bed slope is a hypothetical scenario as it is both difficult and costly to implement at this stage. This scenario was considered important because the sediment hotspot section has a less steep bed slope (S) compared with other sections. For the Arata-Chufa scheme, S was 0.19‰ at the hotspot section and 0.24‰ for the other section. For the Ketar scheme, S was 0.18‰ at the hotspot section and 0.39‰ for the other section. Canal longitudinal bed slope affects the flow velocity, which determines the sediment transport capacity of the canal. The effect of increasing the bed slope of the hotspot section on sediment deposition was simulated for various gradual increments of bed slope until a uniform canal bed slope was attained over the entire canal length.

#### 2.5.4. Scenario 4: sediment flushing during the rainy season

Gravity schemes with a longer feeder canal faces the risk of sediment inflow from overland runoff during the rainy season. Here, change in operation during the schemes' closing season was analysed for its effect on sediment reduction. Allowing a higher continuous flow in the canal during this season might not only maintain the transport capacity of the canal, but could also flush the sediment deposited during the dry season. Thus, scenario four was formulated to evaluate the capacity of the peak rainy season discharge for flushing the sediment deposited in the canal.

A sediment rating curve was developed from discharges and sediment loads measurement at the intake. The rating curve was used to estimate the sediment boundary condition during the rainy season for selected flushing discharges. Sediment load and surface runoff for the overland sediment inflow boundary conditions were computed using the RUSLE model and the rational method, respectively. The gross overland sediment inflow was estimated at 8 $m^3$/year (Arata-Chufa) and 2042 $m^3$/year (Ketar) (Gurmu et al., 2021).

Two additional management options for reducing overland sediment inflow were discussed, although not simulated with the HEC-RAS model because these options only reduce sediment yield from overland flow. These options are diverting overland sediment inflow away from the canals during rains (short-term) and controlling soil erosion (long-term). These scenarios are included in the discussion section as they are important options to reduce overland sediment inflow in the canal.

#### 2.5.5. Sensitivity analysis

Analysing uncertainty is an important aspect in understanding the accuracy and uncertainty of the model. There are two types of sensitivity analysis in the HEC-RAS model, numerical sensitivity and physical parameter sensitivity (HEC, 2022a). Numerical sensitivity requires adjustment of parameters affecting the numerical solution to reach the best solution to the equations. Physical parameter sensitivity involves fine-tuning the flow and morphological properties to evaluate the uncertainty of the model simulations. The HEC-RAS model was run for different computational time steps (1–24 hours) to analyse the numerical sensitivity. Furthermore, the model was simulated for various Manning coefficients to analyse the physical parameter sensitivity. The results of the sensitivity analysis are presented in the supplementary material in Appendix B.

## 3. Results

### 3.1. Calibration and validation of HEC-RAS model

#### 3.1.1. Calibration of the hydraulic model

The unsteady 1D hydraulic HEC-RAS model was calibrated on monthly basis with water level and discharge bathymetry. The HEC-RAS model was calibrated with ranges of Manning roughness (n) values for the lined canal and unlined main canal sections in the Arata-Chufa and Ketar schemes (Table 2). The calibrated Manning roughness value for each canal reach is presented in the supplementary material in Appendix A. The Manning roughness was used to calibrate the water surface profile and the discharges at the head, off-takes and tail end. The calibrated and validated water surface profile and discharge were plotted against observed values to analyse how well simulated values fit the data measured. Fig. 4 shows a plot of calibrated water surface elevation simulated by the HEC-RAS model against water levels measured in the Arata-Chufa scheme.

The model's performance can be considered very good in capturing water surface profile in the canal. The calibrated discharge simulated by the HEC-RAS model was also plotted against discharge measured in the canal. The model again showed very good performance in simulating the canal discharge during both calibration and validation in the Arata-Chufa scheme (Fig. 5).

**Table 2**
Calibrated Manning roughness value for the main canal profiles of Arata-Chufa and Ketar irrigation schemes.

| Canal profile | Canal length (m) | | Roughness (n) | |
|---|---|---|---|---|
| | Arata-Chufa | Ketar | Arata-Chufa | Ketar |
| Lined | 325 | 3705 | 0.013 – 0.02 | 0.012 – 0.02 |
| Unlined | 255 | 3420 | 0.03 | 0.02 – 0.025 |

Fig. 6 shows values for water levels observed in the main canal of the Ketar irrigation scheme plotted against simulated water surface elevation using the HEC-RAS model. The model captured the water surface profile in the downstream reach of the main canal very well and slightly overestimated the water surface profile in the upstream section of the main canal. The Ketar scheme bed level was deformed by the farmers while dredging the sediment for over 30 years, and it was designed in part as concrete and alluvial channel. Such factors affected to arrive at better calibration results. The chute structure between 700 and 1000 m canal bed section resulted in a steep water surface elevation. The residuals of observed and measured water levels at some sections for monthly data are monotonic; however, for a longer time series non-monotonic residuals are observed. Overall, the model performance can be considered good in simulating the water levels in the main canal.

The model's performance was also analysed in simulating the offtake discharge at the intake and downstream end of the main canal. Although there is a slight difference between observed and simulated discharge at the downstream end, the HEC-RAS model performed very well in computing the discharge in the main canal of the Ketar scheme, in both the calibration and validation periods (Fig. 7).

After testing the performance of the model in capturing the water surface profile and discharge in the canal, the performance of the model was also evaluated using error indices. The statistical analysis used to evaluate the performance of the HEC-RAS model is presented in Table 3. The RMSE was close to zero and indicates very good model performance for calibration and validation in both schemes. The root mean square error-observations standard deviation ratio (RSR) ranged between zero and 0.7, and showed very good to satisfactory model performance. The percent bias (PBIAS) of the model was $\leq \pm 15\%$. The PBIAS indicates good model performance for validation in the Ketar scheme. The model showed very good performance in terms of PBIAS for the Arata-Chufa scheme and in the calibration period for the Ketar scheme. The critical $t$ values were higher than the calculated $t$ values except for the validation period in the Ketar scheme. The $t$ statistic shows there is no significant difference between computed values and measured data at a 99.5% confidence level. The Nash-Sutcliffe Efficiency Coefficient (NSEC) ranges between 0.85 and 0.92 for calibration and validation in both schemes.

#### *3.1.2. Calibration of sediment model*

Among the available methods, the Engelund-Hansen transport function, Copeland (Ex7) sorting and armoring method, and Rubey fall velocity approaches yielded better computation of the sediment load in the canal (Fig. 8). The HEC-RAS model in estimating the incoming sediment load and computing the overall sediment deposition performed fairly well (Fig. 9). Hence, we conclude that the HEC-RAs model can be used to analyse scenarios that could reduce sedimentation problems in the SSI schemes.

### *3.2. Results of scenario analyses*

#### *3.2.1. Scenario 1: concrete lining of the canal*

Choosing a Manning roughness is subject to many conditions, and constructing a canal with a specific roughness value is challenging. To compensate for these construction challenges, three Manning roughnesses for smooth, average and rough concrete finishing were therefore chosen. For the Arata-Chufa scheme, the role of concrete lining on sediment deposition was analysed for the section with moderate sedimentation problems, the canal section from division box 1 to pond (Fig. 2a). Lining 100% of this section of the main canal with concrete (n=0.012) could reduce the sediment deposition by about 28%. Lining the alluvial section of the main

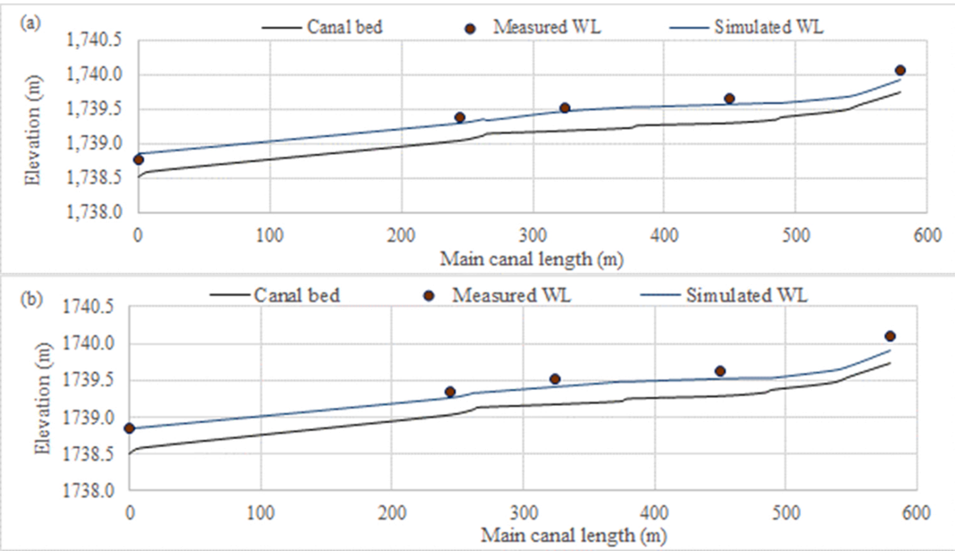


**Fig. 4.** Calibration and validation of water surface profile for the Arata-Chufa small-scale irrigation scheme: (a) calibration from September 2017 to May 2018 and (b) validation from January 2017 to May 2017. The water level calibrated on September 2017 and validated in January 2017.

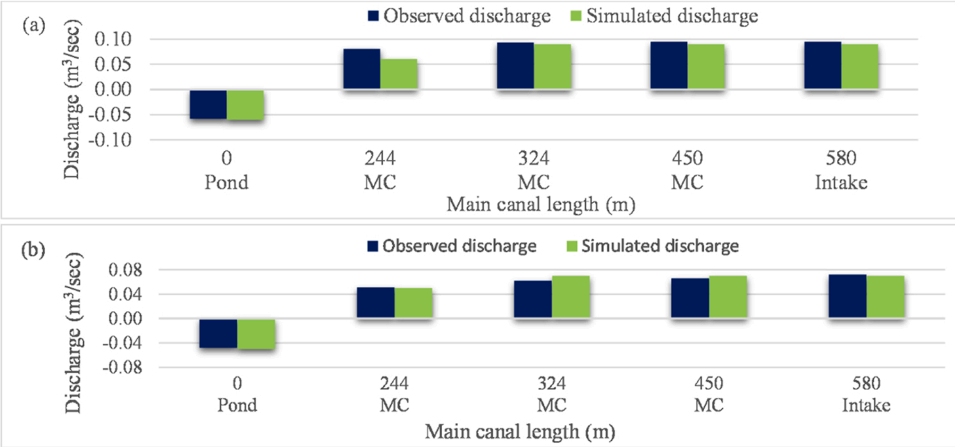


**Fig. 5.** Calibration and validation of discharges of the Arata-Chufa small-scale irrigation scheme: (a) calibration from September 2017 to May 2018 and (b) validation from January 2017 to May 2017.
Note: inflow discharges are considered positive and outflow discharges are considered negative

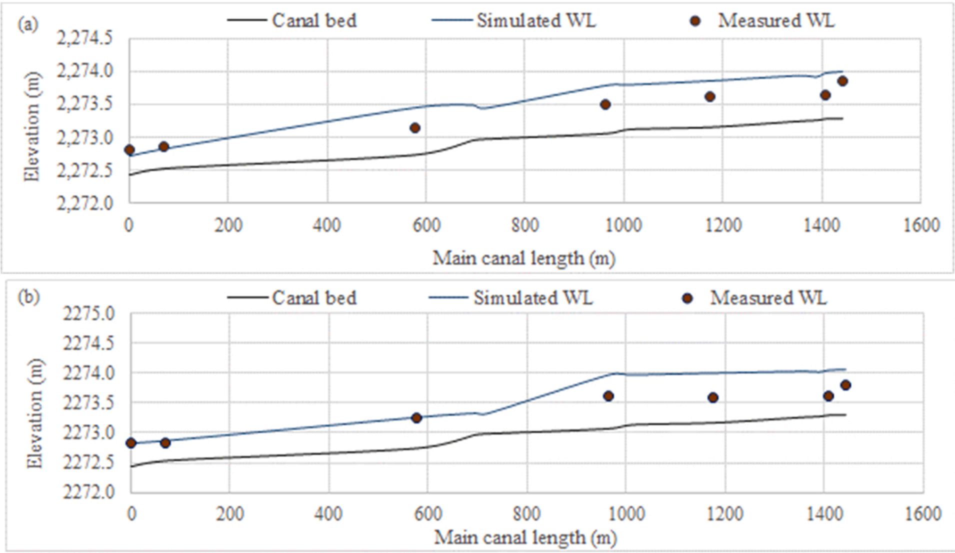


**Fig. 6.** Calibration and validation of water surface profile of the Ketar irrigation scheme: (a) calibration from September 2017 to May 2018 and (b) validation from January 2017 to May 2017. The water level was calibrated on September 2017 and validated in January 2017.

canal with rough concrete finishing (n=0.018) could only reduce sediment deposition by less than 15% (Table 4).

For the Ketar scheme, the hotspot section is located at the downstream end of the main canal (Fig. 2b). The results of the HEC-RAS model showed that lining this section of the main canal would reduce sediment deposition by less than 10%. Lining the alluvial section of the main canal in the Ketar scheme would play a minor role in reducing sediment deposition for the following reasons. First, the unlined part of the main canal in the Ketar scheme is where severe sediment deposition exists, and that section has undergone morphological changes due to desilting practices. Two, the Ketar scheme experiences relatively high overland sediment inflow, and changing the roughness increases the transport capacity during the irrigation season, while overland flow occurs during the non-irrigation season.

### 3.2.2. *Scenario 2: construction of a settling basin*

The settling basin was designed with two options. The first option was merely to store the sediment during the irrigation season without flushing to prevent canal capacity reduction. As peak floods take place during the rainy season, a second option was designed in which a settling basin was combined with sediment flushing. For the Arata-Chufa scheme, a 1.5 m × 3 m × 35 m (depth × width × length) settling basin was considered in the model, with a single desilting campaign annually. For the Ketar scheme, a 2 m × 10 m × 60 m (depth × width × length) settling basin with three desilting campaigns in a year was formulated as a scenario and simulated in

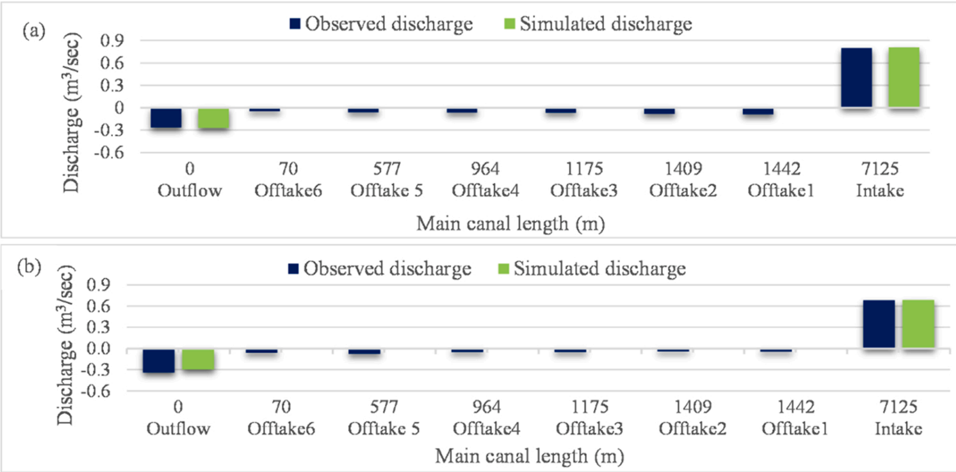


**Fig. 7.** Calibration and validation offtake discharges of the Ketar medium-scale irrigation scheme: (a) calibration from September 2017 to May 2018 and (b) validation from January 2017 to May 2017.

**Table 3**
Result of statistical analysis of model calibration and validation at 95% confidence level for the Arata-Chufa and Ketar irrigation scheme main canal.

| Error Indices | RMSE | RSR | PBIAS | $t_{\text{-calculated}}$ | $t_{\text{critical}}$ | NSEC |
|---|---|---|---|---|---|---|
| Arata-Chufa irrigation scheme $t_{(0.005,4)}$ | | | | | | |
| Calibration | 0.010 | 0.697 | 7.500 | 1.660 | 4.604 | 0.85 |
| Validation | 0.004 | 0.472 | -3.744 | 1.237 | 4.604 | 0.90 |
| Ketar irrigation scheme $t_{(0.005,7)}$ | | | | | | |
| Calibration | 0.038 | 0.194 | -4.253 | 1.973 | 3.499 | 0.92 |
| Validation | 0.073 | 0.489 | -14.447 | 5.400 | 3.499 | 0.88 |

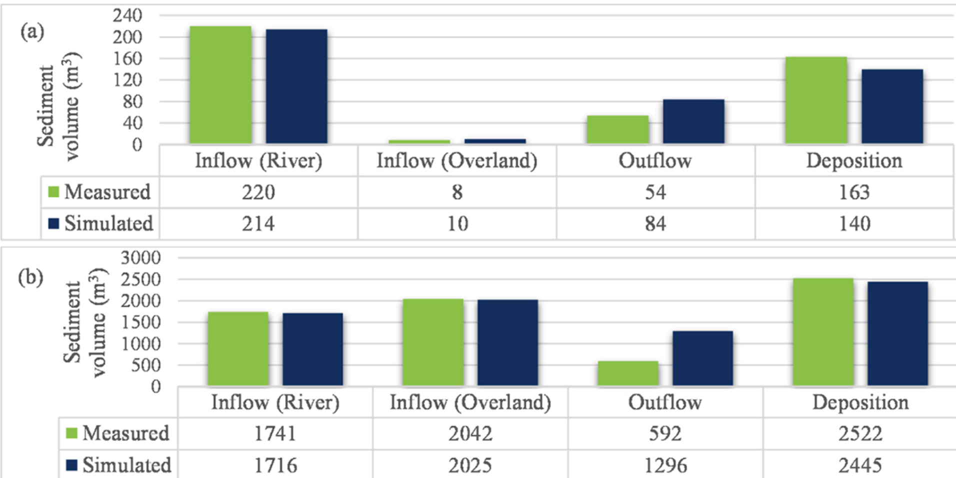


**Fig. 8.** Measured and calibrated sediment load in the main canal of the Arata-Chufa small-scale irrigation scheme (a) and Ketar medium-scale irrigation scheme (b), from September 2017 to August 2018.

the model. The Ketar scheme required a larger settling basin, as the annual river and overland sediment inflow are relatively high.

The settling basins without flushing were designed to trap and store the sediment (mainly from the river) and prevent canal capacity reductions during the irrigation season. The deposited sediment must then be removed at the end of the season. The settling basins reduce the amount of labour required to clean the canals. The settling basins were designed with a maximum capacity of 160 $m^3$ for the Arata-Chufa and 1200 $m^3$ for the Ketar scheme.

The model's results show that the new settling basin at 95 m from the intake is adequate to trap the annual sediment in the Arata-Chufa scheme (Fig. 10a). Combining the new settling basin with a flushing option could reduce sediment deposition by some 63%.

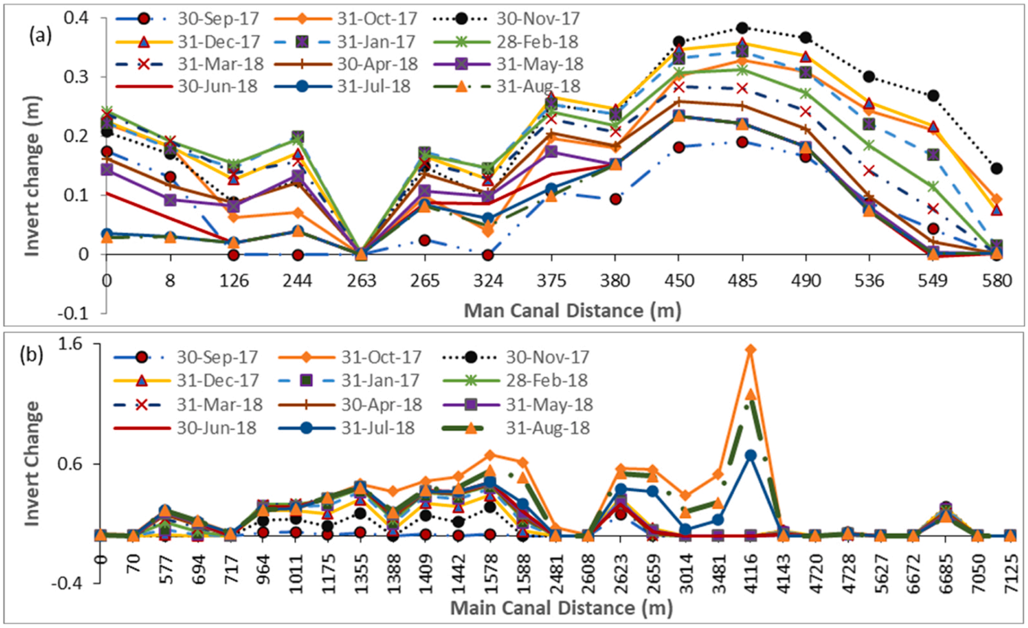


**Fig. 9.** Calibrated sediment invert changes in the main canal of the Arata-Chufa small-scale irrigation scheme (a) and Ketar medium-scale irrigation scheme (b), from September 2017 to August 2018.

**Table 4**
The effect of lining the alluvial part of the canal with concrete on sediment deposition in the main canal of Arata-Chufa and Ketar irrigation schemes for three types of concrete finishing: smooth, average and rough.

| Scenarios | Sediment deposition ($m^3$) | | Deposition decrease (%) | |
|---|---|---|---|---|
| | Arata-Chufa | Ketar | Arata-Chufa | Ketar |
| Current | 130 | 780 | | |
| Arata-Chufa:44% unlined (n = 0.03) | | | | |
| Ketar: 48% unlined (n = 0.02 – 0.025) | | | | |
| Scenario 1: 100% lining (n = 0.012) | 94 | 725 | 27.8 | 7.1 |
| Scenario 2: 100% lining (n = 0.015) | 98 | 721 | 24.7 | 7.6 |
| Scenario 3: 100% lining (n = 0.018) | 110 | 711 | 15.4 | 8.8 |
| Scenario 4: 80% lining (n = 0.012) | 120 | 713 | 7.7 | 8.6 |
| Scenario 5: 80% lining (n = 0.015) | 124 | 709 | 4.6 | 9.1 |
| Scenario 6: 80% lining (n = 0.018) | 127 | 708 | 2.3 | 9.2 |

Building such a settling basin at 3.1 km from the intake would allow the storage of the incoming sediment load from the river and overland flow sources in the Ketar scheme (Fig. 10b). If the new settling basin in the Ketar scheme were combined with sediment flushing, sediment deposition could be reduced by about 42%. The location of the settling basin was chosen by taking into account the formation of major gullies which bring overland sediment into the canal. Thus, as the majority of the sediment comes from the overland flow, particularly in the Ketar scheme, the settling basin serves to trap and flush most of the sediment back into the river.

### *3.2.3. Scenario 3: increasing the canal bed slope*

The average bed slope in the river around the location of the schemes is 1.64‰ for the Arata-Chufa scheme and 1.22‰ for the Ketar scheme. Increasing the bed slope of the main canal was considered for the section of the canal with sediment deposition hotspot. It accounts for 21% and 28% of the main canal length at the Arata-Chufa and Ketar scheme, respectively. This section was deformed during the desilting campaigns during the last 30 years. The effect of reducing sediment deposition by raising the bed slope by 5–30% was analysed (Table 5). Raising the bed slope of the sediment hotspot section by 30% could reduce the sediment deposition by about 16% in the Arata-Chufa scheme and by 9% in the Ketar scheme. The combined effect of lining the canal and increasing the bed slope on reducing sediment deposition was also analysed. Accordingly, the coupled effect of raising the bed slope by 30% and concrete lining (n = 0.012) of the hotspot sedimentation section could reduce sediment deposition by about 47% for the Arata-Chufa scheme and 10% for the Ketar scheme.

### *3.2.4. Scenario 4: sediment flushing during the rainy season*

The rainy season sediment influx from the river was estimated from the sediment rating curve developed from inflow discharges

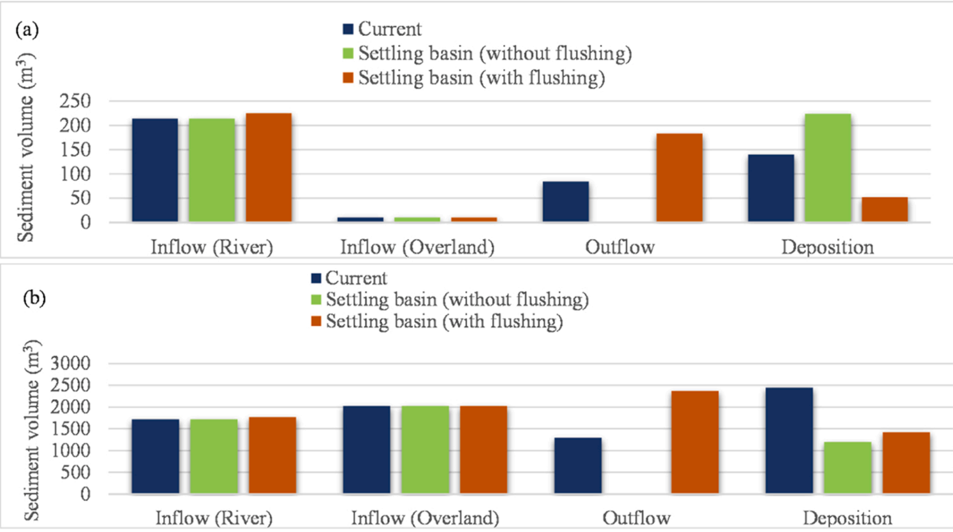


**Fig. 10.** Effect of new settling basin on deposited sediment in (a) the Arata-Chufa small-scale irrigation and (b) the Ketar medium-scale irrigation scheme, with and without flushing options.

and sediment load at the intake. The river sediment influx during the rainy season for selected flushing discharges was estimated at 1.62 tonnes/day for the Arata-Chufa scheme, and at 27.7 tonnes/day for (Q=0.6 $m^3$/sec), and at 43.7 tonnes/day for (Q=0.8 $m^3$/sec) for the Ketar scheme (Fig. 11). The deposited sediment was flushed with a discharge of 0.1 $m^3$/sec in the Arata-Chufa scheme and with a discharge of 0.8 $m^3$/sec in the Ketar scheme.

The surface runoff from the catchments discharging overland sediment to the Arata-Chufa and Ketar schemes was computed by the rational method (Table 6). The computed runoff was used as a boundary condition in the HEC-RAS model to delimit the overland sediment inflow.

The sediment flushing discharges were selected based on the maximum capacity of the main canal at the intakes. The HEC-RAS model results show that flushing the sediment with a peak discharge of 0.1 $m^3$/sec for three months could transport about 82% of the sediment deposited in the Arata-Chufa main canal (Table 7). The sediment could be transported to the pond and field plots via secondary canals.

In the Ketar main canal, flushing with a peak discharge of 0.8 $m^3$/sec for three months could help to remove about 57% of the deposited sediment. As this peak discharge could damage irrigation structures, flushing the sediment with a lesser discharge was also analysed. This revealed that using a discharge of 0.6 $m^3$/sec for three months to flush the deposited sediment allows for the disposal of 50% of the sediment.

## 4. Discussion

Four scenarios of modifying the design (canal characteristics) and changing the operation of the schemes, and two short and long-term scenarios for tackling overland erosion influx (although not modeled with the HEC-RAS) were considered to analyze their effect on reducing sedimentation problems.

### 4.1. *The role of design changes in reducing sedimentation*

Some design options can play a considerable role in reducing sedimentation (Ali, 2021; Munir, 2011; Osman, 2015; Paudel, 2010). For example, a study by Ali et al. (2021), using the HEC-RAS model, reported that the modified permissible velocity design approach yielded the least sediment deposition of all available approaches. However, dissimilar sediment transport behavior can be encountered in irrigation schemes for each design approach employed due to changes in morphological and canal design parameters. The results of the HEC-RAS model of the present study show that the effects of lining the alluvial section of the main canal with concrete differ between the two schemes. Changing alluvial cross-sections into concrete alone plays little to moderate role in reducing sediment deposition for some reasons. First, the sediment transport capacity raised by lining alone would be insufficient to accommodate for the volume of sediment influx. Second, lining would play a moderate role in reducing river sediment than overland flow sediment as other designed parameters are usually fixed considering sediment influx from a river. Third, when the unlined canal section has undergone morphological changes (deepening and widening than the design conditions) due to desilting campaigns, the effect of lining in reducing sediment deposition would be little. In many small-scale farmer-managed irrigation schemes, cleaning the sediment is organized manually. This causes damage to the canal characteristics, such as canal width, depth, side slope, and bed slope, and leads to widening and deepening of the canal, for example, the Ketar scheme. Sometimes this section serves as an artificial sediment settling basin, thereby increasing the desilting campaign load and consuming the majority of the desilting investment costs. Identifying such

**Table 5**
Effect of canal bed slope modification on sediment deposition in the main canals of Arata-Chufa and Ketar irrigation schemes.

| Scenario | New slope | Arata-Chufa scheme Volume of sediment Inflow | Outflow | Deposited | Deposition decreased | New slope | Ketar scheme Volume of sediment Inflow | Outflow | Deposited | Deposition decreased |
|---|---|---|---|---|---|---|---|---|---|---|
| | ‰ | ($m^3$) | ($m^3$) | ($m^3$) | % | ‰ | ($m^3$) | ($m^3$) | ($m^3$) | % |
| Original slope | 0.19 | 214 | 84 | 130 | | 0.183 | 1716 | 936 | 780 | |
| 5% slope increase | 0.200 | 214 | 85 | 129 | 0.8 | 0.192 | 927 | 937 | 779 | 0.1 |
| 10% slope increase | 0.210 | 214 | 86 | 128 | 1.5 | 0.201 | 990 | 947 | 769 | 1.4 |
| 15% slope increase | 0.219 | 214 | 93 | 121 | 6.9 | 0.210 | 907 | 990 | 726 | 6.9 |
| 20% slope increase | 0.229 | 214 | 95 | 119 | 8.5 | 0.219 | 947 | 997 | 719 | 7.8 |
| 30% slope increase | 0.248 | 214 | 105 | 109 | 16.2 | 0.238 | 1008 | 1008 | 708 | 9.2 |
| 30% slope increase & 100% lining (n=0.012) | 0.248 | 214 | 145 | 69 | 47.1 | 0.238 | 1716 | 1019 | 697 | 10.6 |

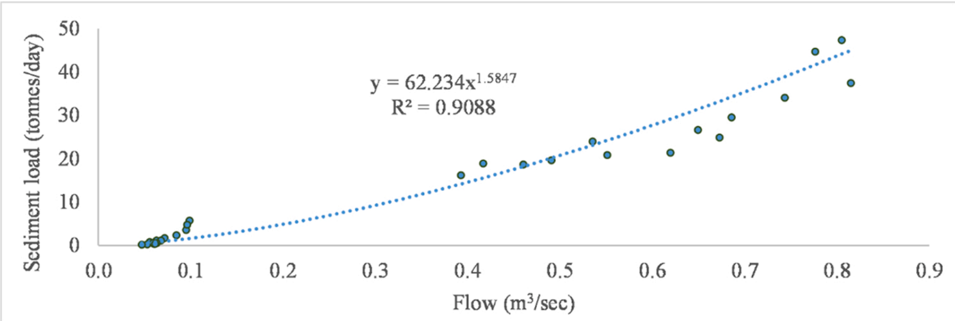


**Fig. 11.** Sediment rating curve developed from annual sediment influx at the intake of Arata-Chufa and Ketar irrigation schemes for estimating the rainy season sediment load for selected flushing discharges.

**Table 6**
Computed runoff and sediment boundary conditions for overland sediment inflow in the HEC-RAS model for sediment flushing scenario from June to August: computed from an area of 1.14 ha for Arata-Chufa and 1082 ha for Ketar (Gurmu et al., 2021).

| Month | Rainfall | | Overland flow (RUSLE) | | Runoff (Rational method) | |
|---|---|---|---|---|---|---|
| | (mm) Arata-Chufa | (mm) Ketar | ($m^3$) Arata-Chufa | ($m^3$) Ketar | ($m^3$/sec) Arata-Chufa | ($m^3$/sec) Ketar |
| June | 107 | 101 | 2.5 | 630.7 | 0.02 | 0.13 |
| July | 128 | 103 | 2.5 | 643.2 | 0.02 | 0.13 |
| Aug | 112 | 123 | 3.0 | 768.1 | 0.02 | 0.15 |
| Total | 347 | 327 | 8 | 2042 | 0.06 | 2.05 |

**Table 7**
Effect of sediment flushing on the removal of the deposited sediment in the main canal of Arata-Chufa and Ketar irrigation schemes.

| Scenarios | Sediment influx River | Overland | Sediment deposition | Deposition decreased |
|---|---|---|---|---|
| | ($m^3$) | ($m^3$) | ($m^3$) | % |
| Arata-Chufa scheme | | | | |
| Current (calibrated values) | 214 | 10 | 140 | |
| Flushing (Q=0.1 $m^3$/s) | 225 | 10 | 25 | 82.1 |
| Ketar scheme | | | | |
| Current (calibrated values) | 1716 | 2025 | 2444 | |
| Flushing (Q=0.8 $m^3$/s) | 1767 | 2025 | 1059 | 56.7 |
| Flushing (Q=0.6 $m^3$/s) | 1761 | 2025 | 1252 | 48.8 |

sediment hotspot sections is essential to prioritize maintenance requirements. Abdelmoaty (2021) reported that the optimum maintenance scenario in terms of hydraulic and economic indicators is achieved when only 50% of the deposited sediment is removed. Thus, organizing sediment desilting campaigns for this hotspot section would be significant to regain the canal capacity. The sediment cleaning activity from an alluvial canal needs to be carefully undertaken so that the sediment transport capacity cannot be altered and the sediment cleaning activity is not aggravated. Fourth, the effect of canal lining on sediment deposition reduction may not be precisely predicted due to the incapability of the HEC-RAS model. The HEC-RAS model is unable to update the roughness values (n) after the initial deposition took place. The roughness of the lined channel will be indistinguishable from the unlined channel once the channel deposits enough sediment to develop an active layer and/or bed form. The canal lining will only reduce the n values until the first deposition and maintaining the concrete channel roughness through the whole simulation, despite deposition, could force the model to over-predict the impact of lining the canal. To overcome this limitation and reduce the uncertainty, the model was calibrated based on the sediment volume balance for a concrete bed channel.

The second option considered to increase canal capacity is to provide a settling basin. The settling basin could increase the canal capacity by more than 30% by reducing the sediment deposition in the canal (Adhi and Ontowirjo, 2021). A similar study by Bhatti et al. (2021) on the effects of a hypothetical settling basin on sediment deposition reduction revealed that some 16% reduction can be attained by using a hypothetical settling basin. The current study designed and simulated equipping a new settling basin with and without a flushing option. The combined effect of the new settling basin and a flushing option could reduce sediment deposition ranging between 42% and 63%. Other similar studies (Chemeda and Dinka, 2020; Namu, 2017; Salmasi et al., 2023) confirmed that settling basins performed better when equipped with frequent flushing option in trapping the sediment and avoiding deposition in the canal, although the exact figures were not indicated. As a second alternative, a new settling basin without flushing option with a capacity to trap one-third to the total annual sediment load with three to a unit annual desilting campaigns, respectively, was provided. Increasing the frequency of desilting campaigns helps to reduce the size of the settling basin; however, the planning depends on how many desilting campaigns the farmers are willing to organize.

The third option analysed was to hypothetically increase the longitudinal bed slope of the sediment deposition hotspot section as lining alone is not adequate to increase sediment transport capacity. Results indicated that increasing the bed slope alone offered limited benefit in reducing sediment deposition. Raising the bed slope by 30% during the irrigation season attained a sediment reduction extending from 9.2% to 16.2% (Table 8). However, raising the bed slope by 30% and lining the canal (n = 0.012) reduced deposition by about 10–47%. These findings justify the work by de Sousa et al. (2022) who claimed significant slope change over time as a key driver for sediment deposition in the Chokwe irrigation scheme in Mozambique. The sediment transport capacity of the irrigation schemes with long headrace canals was compromised to compensate for the elevation difference between the intake and the field plot as the river has a very steep slope than the canal. The average river bed slope in the Arata-Chufa scheme was 1.64‰, while the headrace canal was laid with a slope of 0.16‰. Likewise, the average river bed slope in the Ketar scheme was 1.22‰, while the bed slope of the feeder canal was 0.37‰.

### *4.2. The role of operational changes in reducing sedimentation*

Some specific operational practices enable reducing sediment deposition (Osman, 2017; Theol 2019). For instance, the study by Osman et al. (2017) claimed that operating the scheme depending on actual water needs for the crop during periods when excessive sediment is present in the water could reduce sedimentation by half. Theol et al. (2019) showed that irregular operation of the gates during periods with high sediment load reduces sedimentation by more than 50%. Another study by similar authors (Theol et al., 2020) revealed that opening more upstream gates near the off-taking canal than gates located at the further downstream sections resulted in less sediment deposition in the branch canal. The model results of the current study demonstrated that flushing the sediment during the rainy season could remove more than 50–80% of the deposited sediment depending on the sources/types of incoming sediment. Opening the intake during the rainy season would allow the canal to maintain its transport capacity, in addition to flushing the

**Table 8**
Summary of the scenario analysed for reducing sedimentation in the Arata-Chufa and Ketar irrigation schemes.

| Scenario | Irrigation period | | Sediment deposition | | Decrease in deposition | |
|---|---|---|---|---|---|---|
| | Open | Closed | Irrigation season | Annual | Irrigation season | Annual |
| | Sep-May | Jun-Aug | ($m^3$) | ($m^3$) | (%) | (%) |
| Arata-Chufa irrigation scheme | | | | | | |
| 1. Current | | | 130 | 140 | | |
| 2. Settling basin | | | | | - | - |
| Without flushing | ✓ | | 130 | | - | |
| With flushing | | ✓ | | 140 | - | 62.9 |
| 3. Canal lining | ✓ | ✓ | 94 | 112 | 27.8 | 12.9 |
| 4. Bed slope increase | ✓ | ✓ | 109 | 119 | 16.2 | 15.0 |
| 5. Sediment flushing | | ✓ | | 25 | - | 82.1 |
| Ketar irrigation scheme | | | | | | |
| 1. Current | | | 780 | 2445 | | |
| 2. Settling basin | | | | | | |
| Without flushing | ✓ | | 780 | | | |
| With flushing | | ✓ | | 1422 | - | 41.8 |
| 3. Canal lining | ✓ | ✓ | 725 | 2389 | 7.1 | 28.7 |
| 4. Bed slope increase | ✓ | ✓ | 708 | 2017 | 9.2 | 17.5 |
| 5. Sediment flushing | | ✓ | | 1059 | - | 56.7 |

deposited sediment during the dry season. This is crucial in avoiding the deposition of overland flow sediment, which could be the most dominant sediment source in some schemes, such as Ketar.

While the sediment flushing scenario doesn't incur sediment dredging costs, its implementation depends on multiple factors. One, it depends on the willingness of the farmers to adopt this scenario. The farmers usually prefer to close the intake during the rainy season and follow a rainfed system, assuming there will be high sediment inflow during this season. However, Gurmu et al. (2022) found that farmers' lack of awareness of sources of sedimentation aggravated the sedimentation problem in some schemes. The majority of the sediment could come from overland flow, not via the intake; for instance, in the case of the Ketar scheme. Thus, further discussion is needed with the farmers regarding the implementation of this scenario.

Two, the peak discharge during the rainy season and the heavy materials it transports such as gravel, boulders, and tree branches could damage and block irrigation structures. Thus, numerous factors need to be considered in connection with flushing of the sediment. First, ways must be found to control the peak discharge used to flush the sediment. Second, the flushing activity should be delayed at the beginning of the rainy season or after heavy rainfall. This makes it possible to prevent the entrance of heavy material into the canal. In this case, the farmers may need to manually stir the sediment in order to remove it fully. Third, the sediment should be flushed in phases with periodic evaluation in between. Fourth, the intake and off-taking canal should be designed to withstand peak floods during the rainy season. For instance, the Ketar scheme was designed to showcase such conditions where the first 75 m of the main canal section was built to be fully submerged in floods during the rainy season, and the gate at 75 m from the intake was designed/intended to stop water and sediment inflow to the main canal.

The other crucial short- and long-term operational methods to reduce sedimentation problems are preventing sediment from entering the main canal and limiting soil erosion. Overland sediment inflow is the major driver of sedimentation in irrigation schemes in these areas (Gurmu et al., 2021). Raising the canal embankment to prevent the overland flow sediment from entering the canal could be a reliable short-term approach to reduce sedimentation. Engaging the farmers in soil and watershed management activities to control soil erosion, in the long run, will also help prevent canal sedimentation in a successful and sustainable manner.

Under existing conditions (without the management scenarios), the schemes experience overland sediment inflow, and the inflow volume was computed by the RUSLE model. The overland inflow sediment was then modeled in the HEC-RAS model as a boundary condition of later sediment influx. Fully implementing these short- and long-term management scenarios implies the sediment source in the schemes would be only from the river, as these scenarios prevent overland sediment entrance into the canal. The sediment deposition reduced by implementing these scenarios (preventing overland sediment influx) could be as little as 7% to nearly mounts up to 70% (Table 8).

### *4.3. Uncertainty and limitation of the modelling results*

Sediment models with unsteady flow are highly instable, and the accuracy of the model output depends on the accuracy of cross sectional representation, flow and sediment data. It also depends on the assumptions, limitations, and accuracy of the numerical solution of the model (Williams and Esteves, 2017; Akbari et al., 2012; Gibson et al., 2017). Analysis of numerical sensitivity (computational time step, weir stability factor…) and physical parameter sensitivity (manning's roughness, cross-sectional spacing …) is crucial to reduce the uncertainty of the HEC-RAS model (HEC, 2022a). The HEC-RAS model sensitivity to computational time step was performed for time spans of 1–24 h, and it was observed that the model gave accurate results for the 1 h time step. The reliability of the model's results also depends on the accurate representation of cross-sectional spacing. While a detailed description of the cross-section is important, cross-sections that are too close or too far affect the accuracy of the model output. The HEC-RAS model doesn't have the capacity to update the roughness coefficient after the initial deposition takes place. Such limitation could lead to overpredicting the impact of concrete lining the canal.

The simulation of the flushing was based on an overland sediment inflow data estimated by an erosion model (RUSLE). There are uncertainties in the RUSLE model for estimating the soil loss and sediment yield in the schemes. These include uncertainties due to inaccurate representation of field parameters such as soil and water conservation conditions, gully formations, growing length and types of crop, and terrain complexity (Gurmu et al., 2021). The sediment inflow during the rainy season was computed from the sediment rating curve developed for two years as the rivers are ungagged and longer recorded data is unavailable. This may not precisely represent the sediment inflow during the rainy season. High rainfall intensity during the summer season in these schemes will have a scouring effect which helps to transport the deposited sediment in the canal, leading to discrepancy between measured sediment influx and volume deposited

## 5. Conclusion

The current study investigated measures for reducing sedimentation in SSI schemes suffering from river and overland flow sediment by analyzing how design modifications (canal characteristics) and operational changes can reduce sedimentation, using a hydrodynamic HEC-RAS and an empirical RUSLE erosion model. We analysed the effects of four scenarios on sediment deposition: lining the canal with concrete (roughness), construction of a new settling basin, raising the longitudinal canal bed slope, and flushing the sediment during the peak flood season. Furthermore, we discussed the effect of controlling an overland sediment inflow on canal sedimentation.

Sediment flushing during the rainy season is the most promising alternative to reduce sediment deposition in both schemes, where deposition would be reduced by more than 50–80%. The second option is lining the alluvial part of the canal, particularly in the schemes where sediment mainly originates from the river. There, it could decrease sediment deposition by about 28%. Moreover, these two options are promising because of the low costs involved. Still, it must be pointed out that lining the canal has an insignificant effect on sediment reduction for the scheme in which much of the sediment comes from overland flow.

Building a new settling basin with a flushing option yields more sediment reduction than lining the canal; however, the huge costs it would incur are an obstacle to its implementation. Increasing the longitudinal bed slope of the canal could only reduce sedimentation to a limited extent in the existing schemes. A combination of design modifications, for instance in roughness and bed slope, could help to reduce much of the sediment deposition. Likewise, a combination of lining and increasing the slope (n= 0.012, S= 30%) could reduce sediment deposition by nearly 50%. However, implementation of this option is difficult, as changing the bed slope at this stage in operational schemes is impractical and incurs enormous costs.

To protect the main canal from overland sediment inflow and controlling soil erosion are good short- and long-term alternatives for reducing canal sedimentation. In conclusion, low-cost options to reduce sedimentation problems should focus on operational measures, rather than on design modifications.

## CRediT authorship contribution statement

**Henk Ritzema:** Writing – review & editing, Visualization, Validation, Supervision. **Zerihun Anbesa Gurmu:** Writing – original draft, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mekonen Ayana:** Writing – review & editing, Visualization, Supervision. **Charlotte de Fraiture:** Writing – review & editing, Visualization, Supervision.

## Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: financial support was provided by Netherlands Universities Foundation for International Cooperation (Nuffic) under the auspices of NICHE/ETH197 project for “Capacity Development of HEIs in Small-Scale Irrigation (and Micro Irrigation)”.

## Data availability

Data will be made available on request.

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