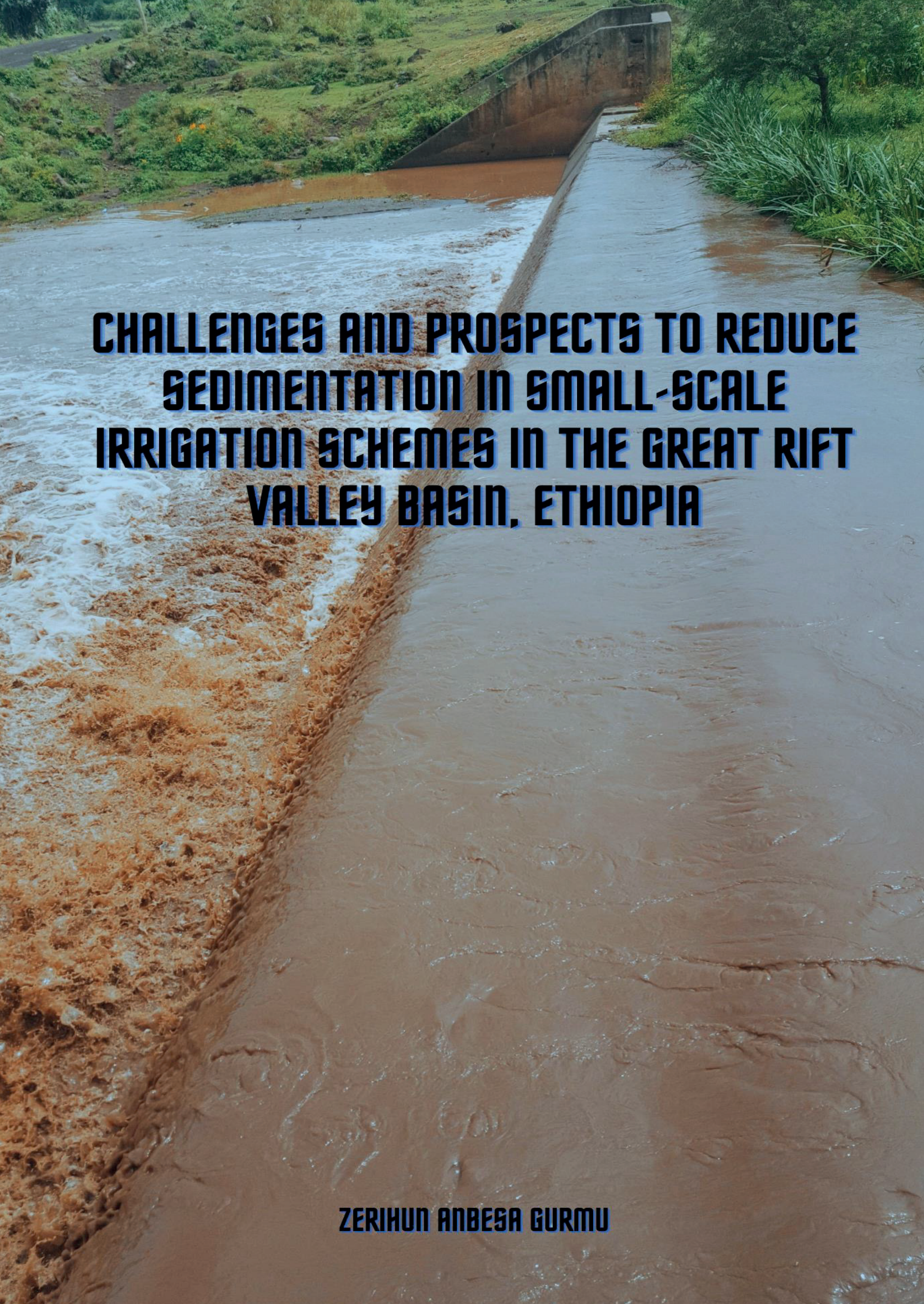

CHALLENGES AND PROSPECTS TO REDUCE SEDIMENTATION IN SMALL-SCALE IRRIGATION SCHEMES IN THE GREAT RIFT VALLEY BASIN, ETHIOPIA

ZERIHUN ANBESA GURMU

Propositions

1. The sedimentation problem in small-scale irrigation is primarily a design problem (this thesis).
2. Farmers' perceptions are more important for tackling sedimentation problems than the engineers' views (this thesis).
3. Local communities are key to overcoming data scarcity in developing countries.
4. Modernization of irrigation schemes without farmers' capacity development is an act of demodernization.
5. Vision and hope are the driving force that transforms a nation.
6. The lack of passion, rather than workload, makes a job cumbersome.

Propositions belonging to the thesis, entitled:

Challenges and prospects to reduce sedimentation in small-scale irrigation schemes in the Great Rift Valley Basin, Ethiopia

Zerihun Anbesa Gurmu

Wageningen, 20 September 2022

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Chapter 1

Introduction

1. Introduction

1.1 Introduction and Background

1.1.1 Global Food Demand and Agricultural Production

The world is facing a monumental challenge to end hunger, malnutrition and poverty. The global population is projected to reach 8.5 billion by 2030, with food demand set to increase by 35% (FAO, 2009; World Bank, 2008a; UN, 2015). To ensure that enough food is available, global cereal production must increase by at least 50% by 2030 (FAO, 2018; World Bank, 2008a). While ending hunger and preventing all forms of malnutrition globally by 2030 is one of the 17 Sustainable Development Goals (SDG), current projections do not look promising for achieving this target (UN, 2015). The number of chronically undernourished people is on the rise. More than 800 million people in the world are undernourished, and some 2.4 billion regularly lack access to food or to a nutritionally balanced diet (UN, 2021; FAO, 2018). The world poverty rate is expected to reach 7% in 2030, substantially missing the target of eradicating poverty entirely (UN, 2021). As poverty and food insecurity are strongly correlated, ending hunger will remain a challenge in the coming decades.

Most food insecure people live in the developing regions of the world, such as sub-Saharan Africa, which has the highest prevalence of hunger at more than 66% (FAO, 2017b; UN, 2021). Increasing agricultural production is the pathway to reduce the number of people impacted by lack of sufficient food and to end poverty. Analyses by the World Bank (2008a) indicate that agriculture does have the potential to satisfy global food demand, if per capita production can be raised, productivity increased and agricultural commodity prices reduced. Since the 1960s, particularly expansion of irrigated agriculture has enabled greater achievements in world cereal production. According to FAO (2018), irrigated agriculture accounts for 40% of global food production, while covering only 20% of cultivated lands. However, irrigated agriculture also consumes a large share of freshwater resources, accounting for 70% of global water withdrawals (Beekma et al., 2021). To double global cereal production and supply enough food in 2030, water demand for agriculture is expected to increase by some 40%. However, acute water scarcity is a threat to the sector's ability to meet the food-supply goal (D'Odorico et al., 2018; FAO, 2018; Hoekstra and Mekonnen, 2012; UN, 2015; World Bank, 2008a).

Already, water scarcity limits the expansion of agricultural systems globally, and it will remain a challenge for future crop production. Some 1.2 billion and 478 million people, respectively, live in river basins characterized by absolute or fast-approaching water scarcity (FAO, 2009; FAO, 2017b; World Bank, 2008a). Thus, higher efficiency agricultural systems are crucial to produce adequate volumes of food with the required nutritional value (Beekma et al., 2021). At the same time, agricultural water management must be integrated with the needs of other, competing sectors, to ensure that agricultural systems are sustainable (de Fraiture and Wichelns, 2010; FAO, 2009).

Irrigated agriculture, however, is notoriously inefficient. Only some 14% of freshwater withdrawals are effectively used for crop production (FAO, 2012). Addressing this inefficiency is a key step towards better allocation of global freshwater resources to meet future food demand. Improved irrigation efficiency is especially important in light of the slowing growth in agricultural water abstraction. Total abstraction for the sector in 2030 is forecast to increase by only 14% from the abstraction quantity in 2000. This limited increase in water withdrawals for agriculture will be caused mainly by water scarcity and competition from other sectors (FAO, 2012). Meanwhile, irrigated lands are projected to expand more quickly than in past decades, pointing to a looming challenge in synchronizing water supplies to irrigated areas (Agide, 2015).

Beyond increased spatial and temporal water use efficiency, raising production efficiency is key to tackle food insecurity. Enabling communities to produce their own food using higher productivity agricultural systems is an important pathway towards the goal of adequate food availability, within the purchasing power of local communities. It is worth noting that agricultural systems in the most food insecure regions exhibit low productivity and underperformance. Sub-Saharan Africa is again an example. The majority of the population here is food insecure, while cereal yields in sub-Saharan Africa are among the lowest in the world (less than 1 ton per hectare) (World Bank, 2008a). Enhancing the performance of irrigated agriculture in such less-developed and emerging regions is vital to satisfy current and future demand for food.

1.1.2 Irrigated Agriculture in Sub-Saharan Africa

Investments in irrigation have transformed agricultural systems and livelihoods around the world (de Fraiture et al., 2014). However, sub-Saharan Africa has failed to share in this success story. The region has consistently exhibited the lowest rate of agricultural expansion and performance. Expansion of irrigated lands in sub-Saharan Africa has remained low, averaging 2.3% annually over the last four decades (You et al., 2011). Irrigated agriculture covers only 4% of the cultivated area in sub-Saharan Africa, compared to 18% on average in the rest of the developing world (World Bank, 2008a). Some 6.3 million hectares (Mha) of sub-Saharan land was under irrigation in 2017, out of 40 Mha of potentially irrigable land (FAO, 2017a). This lack of expansion in the agricultural sector is associated with severe food insecurity in the region, though it is endowed with abundant resources. Increased investment in irrigated agriculture, in addition to creating a pathway to satisfy food demand, could create jobs, as the majority of sub-Saharan Africa’s population depends on agriculture for their living (FAO, 2018; UN, 2021).

Intensifying agriculture is also an important strategy to reduce poverty in sub-Saharan Africa, particularly as the number of poor people has been rising. More than 80% of sub-Saharan Africans live in rural areas, and most countries in the region have agriculture-led economies. For them, increased investment in agriculture can provide a pathway out of poverty and food insecurity (World Bank, 2008a). Irrigated agriculture is a particularly promising area of investment. Sub-Saharan Africa’s irrigated area is projected to double by 2030 (World Bank, 2008a), increasing both the food supply and sector productivity, as irrigated agriculture has been found to produce twice the yields of rain-fed crops (de Fraiture and Giordano, 2014; Mutiro and Lautze, 2015).

In addition to area expansion, raising the performance of irrigated agriculture is vital to ensure that agricultural production and productivity in sub-Saharan Africa are sustainable (Bjornlund et al., 2020b; World Bank, 2008a). In view of the large investment costs associated with large-scale irrigation schemes, and with growing pressure on the region's water resources, particularly due to population growth, and with farm sizes declining, the World Bank (2008a) expects small-scale irrigation (SSI) and rehabilitation of existing irrigation schemes to dominate investments in the region's irrigated agriculture. The potential of SSI in sub-Saharan Africa is estimated at 6.6 Mha, compared to some 1.3 Mha for large-scale irrigation schemes (You et al., 2011). Other reasons why SSI is considered the most promising opportunity for increasing agricultural production in sub-Saharan Africa are design simplicity, low investment cost, easy operation and management, and an overall higher rate of return compared to large-scale irrigation schemes (de Fraiture and Giordano, 2014). Small-scale irrigation schemes have also been found to perform better than large-scale schemes. While large irrigation systems often have a fair share of government control (Bjornlund et al., 2020a), small schemes are often privately owned and operated. According to Mutiro and Lautze (2015), who analysed irrigation schemes in southern Africa, privately managed irrigation performed better than government-controlled schemes. In addition to contributing to food security in the region, SSI can contribute to climate change adaptation, especially for the rural poor, who are the most vulnerable group (World Bank, 2008a). For them, SSI could increase crop yields, enable diversification and help avoid crop failures (Amede, 2015).

Although SSI is widely acknowledged as a preferred investment option and as performing well compared to large-scale irrigation schemes, the overall returns to investments in SSI systems have nonetheless remained less than desired (Abate, 2007; Amede, 2015; Awulachew and Ayana, 2011; Makombe et al., 2017; Mutambara et al., 2016; Mwendera and Chilonda, 2013). Unless SSI performance can be improved, its potential to provide for greater food production in sub-Saharan Africa, and hence to contribute to poverty eradication and food security, will remain unfulfilled. In a study of factors underlying the dysfunctionality of SSI in sub-Saharan Africa, Pittock et al., (2020) argued that SSI had failed due to the disruption of traditional water management practices experienced in the colonial period, when local crops were replaced by export-based crops and farmers were excluded from decision making. Indeed, Bjornlund et al. (2020a; 2020b) argued that concerns related to Africa's biophysical environment and people are secondary, with the major causes of SSI underperformance being related to policy instruments, mode of donor engagement, the farming systems in use and the technologies that were introduced during the colonial period and which African governments continued to promote after independence. During the post-colonial period, expansion of irrigated agriculture was driven largely by the political interests of governments, with keen encouragement and backing by donors, contributing to the poor performance of SSI up to today (Bjornlund et al., 2020a).

The current research acknowledges these historical and political-economic factors behind the underperformance of SSI in Africa, while zooming in on a very overt challenge that farmers confront in their fields: excessive sedimentation. Excessive sedimentation in irrigation structures is related to the problem of soil erosion, which is especially severe in sub-Saharan Africa and forms a major threat to agricultural production there (Tamene and Le, 2015). Already, 65% of land in sub-Saharan Africa is categorized as degraded. Soil degradation and erosion affects 350 Mha (20–25% of the region's total land mass) (Tamene and Le, 2015; Vlek et al., 2008). Soil erosion costs sub-Saharan Africa an estimated US $68 billion annually, and leads to a 3% loss in annual agricultural GDP (Zingore et al., 2015). The East Africa region loses some 2–3% of agricultural productivity annually due to acute soil erosion (World Bank, 2008a), and the region's most severe erosion is found in Ethiopia (Young, 1998). Apart from erosion's direct impacts on farmers' fields, its detrimental consequences extend to the functionality of infrastructures, such as the silting up of reservoirs and clogging of irrigation systems. The economic effects of soil erosion are especially problematic in Ethiopia due to the absence of national capacity to deal with it (Vlek et al., 2008).

1.2 Water Resources Development and Irrigation Potential in Ethiopia

1.2.1 History of Irrigation Development and Its Potential

Ethiopia possesses vast reserves of water, land and labour, all of which are indispensable for expansion of irrigated agriculture. Though assessments differ, the country's irrigation potential has been estimated at some 5.3 Mha (Awulachew and Ayana, 2011). Ethiopia has 12 major river basins with an annual surface runoff of 122 billion cubic meters (BCM) and 6.5 BCM of groundwater potential (Awulachew and Ayana, 2011). The agricultural sector contributes more than 43% of the national GDP and accounts for more than 80% of employment, with some 12 Mha of arable land under cultivation (Adela et al., 2019; Belay and Bewket, 2013; Makombe et al., 2017). Despite vast irrigation potential, crop production in Ethiopia remains dominated by rainfed farming, though rainfall in the region is highly variable. As a result, the agricultural sector has failed to meet the country's demand for food, and nearly half the population is considered food insecure (Kassahun, 2007).

Irrigated agriculture has a long history in Ethiopia. Traditional irrigation practices date back more than two millennia, to pre-Axumite Kingdom times (Gebul, 2021). Conventional irrigation was introduced in the 1950s and used primarily to produce industrial crops on a large scale, particularly for sugar manufacture. Small-scale traditional irrigation systems have nonetheless remained in use to a limited extent in many parts of the country, though they do not contribute significantly to national crop production. Use of modern irrigation for cereal crops is of rather recent origin in Ethiopia (Gebul, 2021), triggered by the devastating drought that occurred in the country in 1984–1985. Application of irrigation systems to produce cereal crops was adopted starting in the latter 1980s as a pathway to food security. In 1991, however, Ethiopia underwent a regime change, and 1991 to 1995 is considered a transitional period in which the development of irrigation was interrupted (Gebul, 2021).

Interest in irrigation development reawakened starting in 1995, after which the Ethiopian government orchestrated a series of programmes and plans that included expansion of irrigated agriculture (Gebul, 2021). Among these were the Sustainable Development and Poverty Reduction Program (SDPRP), which extended from 2002 to 2005; the Plan for Accelerated and Sustainable Development to End Poverty (PASDEP), from 2005 to 2010; the Growth and Transformation Plan I (GTP I), from 2010 to 2015; and the Growth and Transformation Plan II (GTP II), from 2015 to 2020. Over the three decades from 1991 to 2019, according to (Gebul, 2021), provision of technologies for medium and large-scale irrigation schemes led to an increase in such irrigated area from 30,400 ha to 540,000 ha, while lands irrigated using SSI infrastructure expanded from 64,000 ha to 2.528 Mha. In Ethiopia, irrigation schemes with a command area less than 200 ha are classified as small-scale, while medium-scale systems have a command area between 200 ha and 3,000 ha and large-scale systems have a command area greater than 3,000 ha.

1.2.2 Performance of Irrigated Agriculture in Ethiopia

Despite progress in expanding irrigated lands, only half of the expansion targets set in the government plans were achieved. This is due in large part to limited implementation capacity (Gebul, 2021; NPC, 2016). Furthermore, it warrants mention that the land area actually irrigated is substantially less than the reported figures, as the latter indicate areas equipped with irrigation technologies, while in many cases these have fallen into disrepair and disuse due to incomplete construction or malfunctioning of completed components. Capacity limitations are reflected not only in inability to achieve plan targets but also in the quality of studies, designs and construction outcomes. Moreover, there has been an overemphasis on scheme construction, with a relative lack of consideration for irrigation system management. This has undermined the operation and performance of many of the schemes (Gebul, 2021).

Awulachew and Ayana (2011) attributed the failure to achieve plan targets and the many operational problems encountered in completed irrigation systems to lack of strong national institutions for irrigation development and management. In the country, large and medium-scale irrigation schemes are implemented by federal and regional government offices, while SSI development is solely the responsibility of regional governments. While there are formal institutions charged with irrigation development and management, these are of rather recent origin and were not founded explicitly for irrigation development purposes. As such, the Irrigation Development Commission, founded in 2018 under the Ministry of Water, Irrigation and Electricity, has a mandate to develop and manage large and medium-scale irrigation schemes. Regional governments have the authority to establish similar institutions concerning SSI schemes. One such regional institution was the Oromia Irrigation Development Authority (OIDA), founded in 2000, which played a substantial role in development of SSI schemes in Oromia regional state. However, this authority was dissolved in 2019. Currently, irrigation development is implemented by the regional states’ respective water, irrigation and energy development bureaus.

The continuous restructuring of the institutions in charge of irrigation development and management has led to a loss of institutional memory and data, which now constitutes a major obstacle to knowledge and skills transfer. Another daunting problem is the lack of a centralized institution that keeps records and tracks the history of irrigation development in the country; as such records could help today's practitioners learn from the past (Gebul, 2021). The consistent focus on expansion of new irrigation schemes, while those previously operationalized underperform or lie abandoned, testifies to a lack of regard for – or access to – lessons from past efforts. As yet there has been little attention to rehabilitation of deteriorated schemes. However, as the investment cost of new irrigation schemes is high, revitalization of underperforming and dysfunctional systems to optimize their performance could be a promising pathway to enhance the performance of irrigated agriculture in the country. This, however, requires strong institutions with the capacity and resources to take a leading role.

In addition to the institutional constraints, dysfunction and underperformance of irrigation systems in Ethiopia is caused by biophysical factors, particularly land degradation and erosion, which are common across sub-Saharan Africa. According to Aynekule et al. (2009), nearly half of Ethiopia's arable land (60 Mha) is under moderate erosion risk, while a quarter of arable land is under severe erosion risk, and 2 Mha has reached a point of no return (it can no longer be rehabilitated). Ethiopia loses some 25,000 ha of arable land annually, with mean soil losses estimated at 42 tons/ha/year (FAO, 1986). Soil is lost at a faster rate than soil formation (1.5 million tons/year), leading to a net loss of soil, which costs the country an estimated US $11.7 million per year (FAO, 1986; Mekonen, 2005). In addition to the impact on farmers' fields, soil erosion has far-reaching consequences for the sustainability of water resources, reservoir infrastructure and irrigation schemes, due to the resultant problem of excessive siltation. Concern about the sustainability of irrigated agriculture in Ethiopia (both existing and new schemes) has therefore led to urgent calls for intervention to control soil erosion. Whether designing new irrigation schemes, or rehabilitating existing infrastructure, due consideration must be given to sediment transport and management, to optimize water use efficiency and limit irrigation scheme underperformance.

1.3 Problem Statement

The persistent underperformance of irrigated agriculture in sub-Saharan Africa has meant that the expected returns on investments in irrigation technology seldom materialize. Meanwhile, irrigation scheme failure and underperformance undermines the region's ambition to achieve food security, despite its high prevalence of hunger and acute poverty. Irrigation expansion in sub-Saharan Africa has been caught in a vicious cycle, with new systems being constructed while old systems underperform or lie disused – though this cycle is increasingly unsustainable due to resource scarcity. There are many reasons for irrigation scheme underperformance. However, a primary factor causing irrigation structure failure and underperformance is excessive sedimentation (Abate, 2007; Amede, 2015; Awulachew and Ayana, 2011). Excessive sediment deposition in irrigation canals reduces system discharge capacity by up to 40% (Belaud and Baume, 2002), thereby engineering water scarcity. While frequent desilting campaigns are required to maintain an optimum supply of water in feeder canals, desilting brings additional costs. Yet, failure to perform the necessary dredging work results in system underperformance, and sediment accumulation can even undermine systems' structural integrity (Ahmed et al., 2018).

Sedimentation is ultimately a function of soil erosion on the surrounding lands. However, its severity in a particular irrigation scheme also depends on faults in design and problems in operation and maintenance (O&M). The fact that sediment transport in irrigation canals is not entirely understood hinders appropriate design (Nestore et al., 1998). Irrigation system designers must rely on sediment transport theories based on river flows (Depeweg and Mendez, 2002; Nestore et al., 1998). They typically assume uniform, steady-state and equilibrium conditions in irrigation canals, though such conditions are seldom found in built channels due to the presence of dynamic gate movements and variability of incoming sediment and discharge (Depeweg et al., 2016; Nestore et al., 1998). To estimate sediment transport in irrigation canals, flume data and case studies from the specific region of interest may be used. However, these must be validated, and the situations in which they are applicable remain limited (Depeweg et al., 2016; Osman, 2015).

There is no irrigation system design method that simultaneously allows for (1) computations with flexible water delivery, (2) estimation of the incoming sediment quantity and (3) optimization of O&M (Munir, 2011; Paudel et al., 2010). In sum, while everywhere in the world it is challenging to design irrigation schemes that can withstand severe sedimentation, the challenge is greatest in developing countries (Ghumman et al., 2006). This is mainly due to limitations of resources, knowledge and design tools in these countries. Numerous irrigation schemes display faulty designs due to these limitations, and in many cases design faults even aggravate sedimentation issues. How can irrigation scheme designers overcome the inherent limitations and difficulties that lead to design faults which cause or amplify sedimentation problems, particularly in irrigation schemes in least developed and emerging countries?

Beyond design, irrigation scheme O&M is another key factor in determining the extent of sedimentation problems. Inadequate O&M is said to be responsible for more than 50% of sediment deposition in feeder canals (Osman et al., 2017; Theol et al., 2019b). The O&M rules set for an irrigation scheme need to clearly state the required frequency of desilting campaigns to maintain canal transport capacity. Delayed desilting, in addition to impairing the flow of water in canals, leads to increased difficulty of sediment dredging work (Belaud and Baume, 2002). Some of the problems encountered in scheme O&M emanate from the irrigation planning and development process. Here, a technology mismatch is often observed, with the involved farmers lacking the technical skills or the resources needed to perform the required O&M activities. Manual dredging of sediment by farmers may be impracticable due to the size of the structures (e.g., ponds or sediment settling basins). Or, farmers' lack of technical capacity to maintain structures such as intakes and gates may jeopardize scheme operation such that sedimentation problems are worsened.

Another often-overlooked aspect is overland sediment inflows into irrigation works. In some cases, overland inflows contribute the majority of the sediment in feeder canals. The potential for overland sediment inflows is often overlooked at the design stage as well, despite schemes being located in areas known to be affected by severe erosion. Very large quantities of sediment may enter canals from the surrounding lands, requiring adequate measures and capacity to manage it.

In recognition of the impacts of excessive sedimentation on performance and the design and management issues that arise in dealing with sediment in irrigation infrastructures, the current study (1) investigated the perceptions of stakeholders regarding sedimentation problems, (2) quantified and estimated sediment inflows, (3) monitored desilting campaigns and (4) analysed the role of design modifications and changes in O&M practices in reducing sedimentation problems in SSI schemes in Ethiopia.

1.4 Rationale for the Study

Excessive sediment deposition is recognized as a primary cause of underperformance and failure of irrigation schemes across sub-Saharan Africa. Excessive sedimentation increases O&M costs and problems of water undersupply. Sediment deposition problems are particularly severe in countries with limited resources to address the issue. In Ethiopia, though resources are scarce, investment in irrigated agriculture is vital to advance food security and alleviate poverty. Yet, irrigation expansion here is hampered by population pressure, diminishing farm sizes, increasingly scarce natural resources and the changing climate. Indeed, irrigated systems today must be designed and operated with the environment and sustainability foremost in mind. Despite these daunting challenges, the only way to produce enough food is by enhancing the efficiency and performance of irrigated agriculture. For this, the problem of excessive sedimentation must be addressed.

The research presented in this thesis assesses the extent of the problem of excessive sedimentation and investigates ways of reducing sediment deposition in SSI schemes situated in regions of severe soil loss in sub-Saharan Africa, in particular, in Ethiopia.

1.5 Research Hypothesis

A lack of data and substantial knowledge gap limit our understanding of sedimentation problems in irrigated agriculture in least-developed and emerging countries. At the same time, much knowledge is embedded in communities of practice, where local farmers have implemented irrigation for decades and developed tacit knowledge for managing irrigated agriculture, including sedimentation. Thus, participation of local users and combining scientific findings with local tacit knowledge can be considered a promising approach to co-generate actionable knowledge to overcome data scarcity challenges and enhance understanding of sedimentation problems in developing countries.

Although irrigation schemes fed by sediment-laden water face sedimentation challenges, the problem is aggravated by design issues and faults and poor operation and maintenance practices. If an irrigation system is conceived and implemented in a top-down manner, farmers using the constructed system may be unprepared or unable to perform the needed maintenance. By both modifying design parameters and changing operating practices, sedimentation problems may be reduced in existing irrigation schemes. To determine more optimum design and operation, hydrodynamic sediment transport models can be used.

1.6 Research Objectives and Questions

Excessive sedimentation undermines the functionality of SSI schemes around the world, resulting in underperformance and increased O&M costs, particularly in regions that can least afford them. The overarching objective of the current research was therefore *to assess the extent of sedimentation challenges, to estimate their magnitude and to analyse how sedimentation problems might be overcome through in-depth study of two SSI schemes in Ethiopia using a socio-technical approach*. The main research question is the following:

> *What is the extent of the sedimentation problem, and how can it be addressed and the overall performance of small-scale irrigation schemes enhanced employing a socio-technical study?*

To address this question, four specific research objectives were derived:

1. To assess the perspectives of stakeholders on sediment management and their roles in the management of excessive sedimentation in SSI schemes
2. To quantify the magnitude and sources of sedimentation in SSI schemes
3. To estimate overland sediment influx and its drivers in farmer-managed irrigation schemes
4. To analyse ways of addressing sedimentation problems in SSI schemes in order to reduce O&M costs applying a hydrodynamic sediment transport model

This thesis addresses these objectives successively. First, the perspectives of stakeholders regarding sediment management and the roles stakeholders play in managing excessive sedimentation is investigated in two SSI schemes. Indeed, involvement of many actors is required to effectively manage excessive sedimentation and ensure the sustainability of irrigation schemes. Successful interventions to tackle excessive sedimentation require involved actors to have a general understanding of the contributors to and severity of the problem. This can be promoted with knowledge sharing and learning from best practices. Many SSI schemes, while operating below maximum capacity, survive for many years despite problems of excessive sedimentation. The durability of these schemes could point to effective strategies for overcoming sedimentation problems, while closer investigation of users' experiences with these schemes might demonstrate typical challenges. As data scarcity is a major problem in addressing sedimentation problems in SSI schemes, this research undertook to engage with concerned stakeholders to overcome the lack of data availability. Community participation, apart from serving as a source of data, played two main roles in the current research: (1) enabling investigation of factors preventing schemes from achieving optimum performance; and (2) providing indications of why and how some schemes continue to perform satisfactorily, even under conditions of excessive sedimentation – thus pointing towards possible best practices. Combining these two, the first research question is formulated as follows:

> *What are the roles and perceptions of stakeholders regarding sedimentation management, and how severe is sedimentation in specific cases of operable SSI schemes (RQ1)?*

After becoming acquainted with the contributions and modalities of engagement of various actors in sustaining SSI schemes with excessive sedimentation, a next challenge is to obtain data with which to evaluate the extent of sedimentation problems. Data scarcity, as noted, stands in the way of understanding the severity of excessive sedimentation in SSI schemes and finding strategies to resolve these. Moreover, lack of adequate and reliable data is a common challenge facing irrigation expansion in developing countries. In particular, lack of historical data on sediment influx into small-scale schemes has hindered analysis of sediment budgets. Data is also largely unavailable or incomplete on sediment management practices, such as desilting campaigns (e.g., frequency, monitoring and quantity of sediment dredged), O&M rules and measures taken to reduce sedimentation. While event-based or seasonal data may be available in some cases, these do not necessarily reflect the extent of the sedimentation challenge and may in fact suggest unsound strategies to overcome the problem. While formal institutions in developing countries may lack the resources to effectively collect and organize many years' data from local schemes, community participation can provide a solution for acquisition of historical data to a limited extent. This research used community participation to obtain measurement data with which to evaluate the extent and management of sedimentation problems in SSI schemes. This data was applied to answer the following research question:

> *What are the sources of sediment in SSI schemes, how much of that sediment comes from the river and how has it been managed (RQ2)?*

Rivers in Ethiopia are known to carry heavy sediment loads, contributing greatly to the sedimentation problems observed in local irrigation schemes. Sediment control and management structures are designed with consideration for the quantities and types of sediment transported by rivers. Much less consideration has been given to overland sediment flows – although the contribution of sediment conveyed in surface runoff is massive in Ethiopia, due to the severe upland land erosion and the furrow system of farming widely practiced. It is therefore vital to accurately quantify the amount of sediment entering irrigation structures with overland flows from the surrounding lands, while also delineating the contributing land areas and identifying gully hotspots.

Many approaches are available to estimate soil losses and the corresponding sediment yield. Most of these, however, produce highly uncertain results, due to lack of reliable data across both space and time. As the case study areas for this research were also characterized by limited data availability, we chose a soil loss estimation method that allows model input parameters to be validated using field-collected data. The revised universal soil loss equation (RUSLE) model was selected for three main reasons: it allows prediction of soil losses from small catchments, it allows cell-by-cell computation of soil losses and it accepts input data from a global database. RUSLE was used to answer the following research question:

> *How much is the influx of overland sediment inflow in SSI schemes and what are the underlying causes of the overland sediment influx (RQ3)?*

This research examined two SSI schemes in an effort to quantify the extent of their sedimentation problems and the implications of these for operational costs. However, scrutinizing approaches that might reduce sediment inflows is cumbersome, as physically testing individual approaches on the ground is impractical. Hydrodynamic sediment transport models were therefore applied as a convenient means to evaluate the effect of measures to influence sediment transport behaviour in canals, though their application is associated with uncertainties.

Structural and non-structural measures can be applied to reduce sedimentation in irrigation schemes. Because the overarching aim of sediment control measures is to reduce O&M costs, their implementation should not be costly. Perhaps the best way to sustainably control sedimentation in irrigation works is to prevent the problem at its source – soil erosion. Furthermore, consistent implementation of measures to prevent excessive sedimentation problems in irrigation schemes depends on the willingness of farmers and other concerned stakeholders to carry out the require tasks. Hence, the final research question concerns practical measures to reduce sedimentation problems in the two studied schemes, for which the Hydrologic Engineering Center's River Analysis System (HEC-RAS) hydrodynamic model was used. The associated research question is the following:

> *Can changing design parameters and operational practices reduce sediment deposition in SSI schemes, according to the hydrodynamic HEC-RAS model, and what is the most efficient approach to reduce sedimentation (RQ4)?*

1.7 General Methodology

The current study focused on two SSI schemes, Arata-Chufa and Ketar, situated in the Great Rift Valley Basin of Ethiopia. Arata-Chufa is a 100 ha SSI scheme serving 324 beneficiaries. The Ketar scheme serves 1,074 beneficiaries. It was built in three sections, from upstream to downstream: Ketar 1 (110 ha), Ketar 2 (200 ha) and Ketar 3 (120 ha). Very little data was available on both Arata-Chufa and Ketar for studying sedimentation problems and exploring options to overcome the challenges. A range of approaches was therefore employed to overcome the data scarcity problem. These included reliance on local stakeholders as a data source, field data collection and measurements conducted in three years, as well as laboratory analysis. A socio-technical approach was used to analyse interventions to reduce sedimentation problems in the SSI schemes. Key methods were participatory rural appraisal (PRA) and modeling using the revised universal soil loss equation (RUSLE) and the hydrodynamic HEC-RAS sediment transport model. Figure 1.1 presents a simplified conceptual framework for the current research. Details of the methodological approaches and irrigation schemes are presented in the respective chapters.

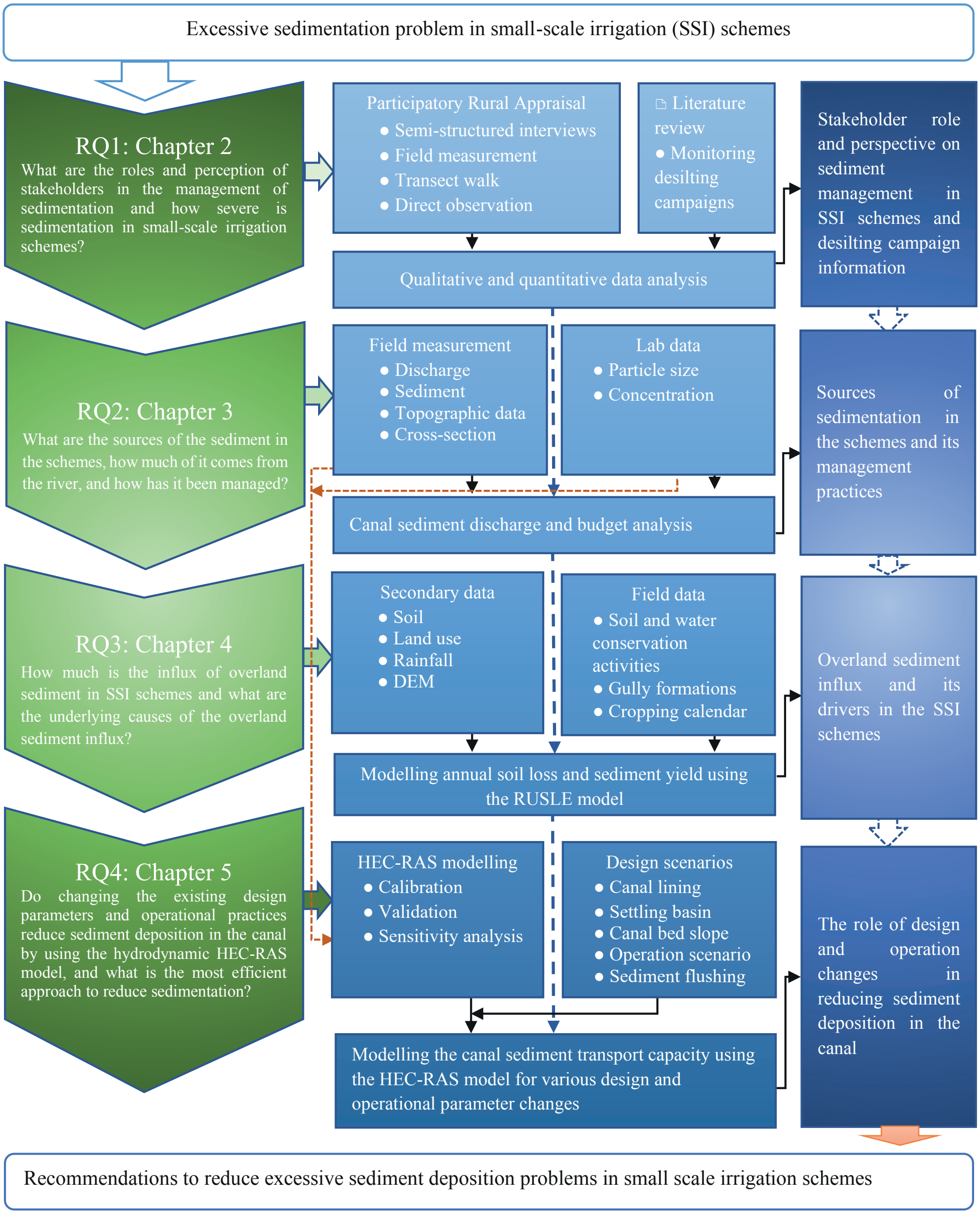

Figure 1.1: Conceptual framework used in this research to investigate measures to reduce sedimentation problems in small-scale irrigation schemes

1.8 Structure of the Thesis

This thesis is structured in six chapters. Following this introduction to the problem of excessive sedimentation in SSI schemes and the importance of addressing it for food security and poverty eradication, each of the subsequent chapters delves into an individual research objective/question.

Chapter 2 examines the perceptions of various stakeholders of the severity and management of sedimentation problems and their roles in addressing these. The chapter seeks evidence on the ground to verify claims from the literature regarding the underperformance and failure of irrigation schemes due to excessive sedimentation. It also investigates factors that might contribute to more sustainable irrigated agriculture in areas where excessive sedimentation is a particular problem and resources are scarce.

Chapter 3 measures, quantifies and presents the extent of sedimentation problems in the two studied SSI schemes for three years. These schemes were affected not only by river sediment but also by sediment influx from overland flows. The analysis provides evidence of the severity of these sources in association with the excessive sedimentation problems faced in these schemes and their effect on irrigation performance.

To capture the full extent of the problem of excessive sedimentation, Chapter 4 presents a modeling study using the revised universal soil loss equation (RUSLE) to quantify overland sediment influx, and hence the contribution of overland flow to overall sediment deposition in the schemes.

The case study schemes were designed only considering sediment from the river source. However, the analyses indicate that much of the sediment in fact comes from surface runoff. Chapter 5 presents and discusses the hydrodynamics of sediment transport modeling in irrigation canals, seeking in particular, to identify ways to reduce excessive sedimentation problems by coupling river and overland flow sediment.

Chapter 6 summarizes the key findings of the study, considering the contributions of the research to the literature and its societal relevance, especially with regard to policy implications for the expansion of irrigated agriculture in developing regions affected by severe erosion and resource scarcity. Limitations of the work are considered, as well as avenues for further study.

2

Chapter 2

Stakeholder Roles and Perspectives on Sedimentation Management in Small-Scale Irrigation Schemes in Ethiopia

This chapter is based on:
Gurmu, Z. A., Ritzema, H., de Fraiture, C., & Ayana, M. (2019).
Stakeholder Roles and Perspectives on Sedimentation Management in
Small-Scale Irrigation Schemes in Ethiopia.
Sustainability, 11(21), 6121. doi:10.3390/su11216121

2. Stakeholder Roles and Perspectives on Sedimentation Management in Small-Scale Irrigation Schemes in Ethiopia[1]

Abstract: Irrigated agriculture, particularly small-scale irrigation (SSI), is a mainstay for sustainable livelihoods in the developing world. In Ethiopia, SSI sustainability is threatened mainly due to excessive sedimentation. Stakeholders' perceptions of the causes of sedimentation and how they sustain SSI under excessive sedimentation conditions were investigated in two SSI schemes in Ethiopia. A participatory rapid diagnosis and action planning was implemented, consisting of a literature review, participatory rural appraisal, and semi-structured interviews. Results show that farmers slightly differed in perception of excessive sedimentation drivers. Farmers reported design problems as the main cause of excessive sedimentation (64%), followed by poor operation and maintenance (O&M) practices (21%) and external factors (15%). In contrast, 62% of the interviewed engineers indicated erosion and irrigation technologies as the main causes of excessive sedimentation, while few reported poor design (13%). In addition to an intensive desilting campaign, farmers delayed the start of the irrigation season to avoid the intake of highly sedimented water. Local social capital and knowledge appeared to be more important than formal knowledge and blue-print institutions for dealing with sedimentation problems. Well-organized structure and extra time devoted by famers were vital for SSI sustainability. Integration of the farmers' knowledge with that of the engineers could yield more effective ways to deal with sedimentation problems.

Keywords: Small-scale irrigation; Sedimentation; Farmers; Water User Association (WUA); Indigenous knowledge; Perception

[1] This chapter is based on: Gurmu, Z. A., Ritzema, H., de Fraiture, C., & Ayana, M. (2019). Stakeholder Roles and Perspectives on Sedimentation Management in Small-Scale Irrigation Schemes in Ethiopia. *Sustainability, 11*(21), 6121. doi:10.3390/su11216121

2.1 Introduction

Irrigated agriculture is a prime sector to ensure food security, alleviate poverty, and promote economic development in the developing world (de Fraiture et al., 2010). Small-scale irrigation (SSI) schemes in particular make a massive contribution to national economies in many developing countries, while also serving as an incubator for collective action (Amede, 2015). Nonetheless, “traditional” SSI schemes are largely overlooked by states (de Fraiture and Giordano, 2014). Governments prefer the development of more “modern” irrigation schemes, considering “farmer-led” irrigation schemes “inefficient”, “unproductive” and “traditional” (Beekman et al., 2014; de Bont et al., 2019; Veldwisch, 2019). To date in Africa, however, the total area under SSI schemes is much larger than that under medium- and large-scale irrigation (Beekman and Veldwisch, 2016; de Fraiture and Giordano, 2014).

In Ethiopia, traditional SSI schemes accounted for 80% of the total irrigated land in 2018/2019 (MoWIE, 2019). Ethiopia’s largest region, Oromia Regional State (28.66 million ha), had 612 modern irrigation schemes in 2016/2017, compared to 9,379 “traditional” and 63,523 pump irrigation schemes, according to data from the Oromia Irrigation Development Authority (OIDA) (OIDA, 2016). However, the contribution of all these schemes to Ethiopia’s national economy has been much diminished due to the underperformance of the systems (Haile, 2015; Lankford, 2004). Indeed, most are either non-functional or operate far under their potential (Awulachew and Ayana, 2011; Dejen, 2012). For instance, in Oromia Regional State alone, 109 (18%) of the modern schemes and 8,508 (13%) of the pump schemes were reported to be inoperative or semi-functional in 2017 (Figure 2.1). Several explanations have been given for this underperformance, such as design failure and poor design, excessive sedimentation in the headwork and main canal, scouring damage, poor scheme management, and inferior institutional set-up (Abate, 2007; Aberra, 2004; Amede, 2015; Awulachew and Ayana, 2011; Yohannes et al., 2019).

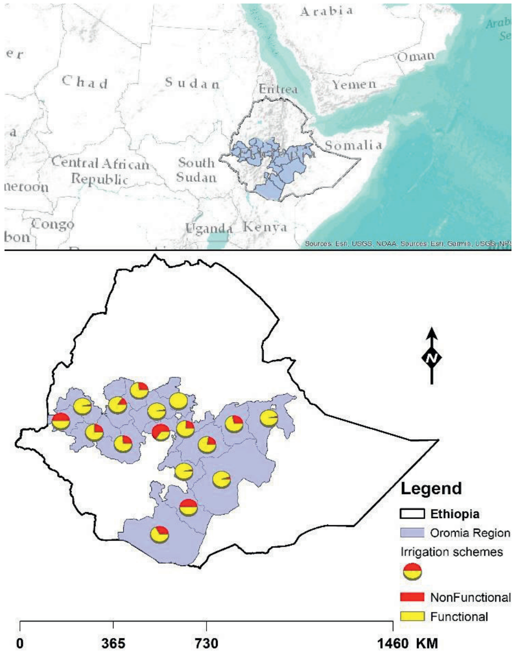

Figure 2.1: Functional and non-functional irrigation schemes in Oromia Regional State, Ethiopia (source: Oromia Irrigation Development Authority, 2016).

Ethiopia experience the most serious erosion in the world (Erkossa et al., 2015; Gelagay and Minale, 2016; Haregeweyn et al., 2017), one of the most significant adverse environmental problem in developing countries. Excessive sedimentation in irrigation systems gradually blocks the flow of irrigation water, causes water stress and unfair distribution (Theol et al., 2019a), damages infrastructure, and may trigger the complete collapse of irrigation systems. Since irrigation is a major consumer of water (He et al., 2018; Li et al., 2019), the loss of water due to damage to infrastructure by excessive sedimentation results in a decline in water availability and increased competition among different water uses and users. The management of sedimentation in irrigation systems requires large and continual maintenance and operation investments (Depeweg and Méndez, 2002). In farmer-managed irrigation schemes, excessive sedimentation places a huge maintenance burden on farmers, in addition to their other farming activities (Figure 2.2). Irrigation canals with excessive sedimentation are generally collectively dredged, with farmers who are perceived as not doing their share of the work sanctioned. This, however, may generate farmer dissatisfaction and conflicts, possibly undermining collective action and social interaction.

Figure 2.2: Farmers dredging sediment from a main canal (sediment hotspot section) at Ketar irrigation scheme (August 2017).

Farmers introduced irrigation systems and through decades of experience have developed ways of dealing with excessive sedimentation (Veldwisch, 2019). Nonetheless, states have tended to overlook this indigenous knowledge. Instead, they have turned their focus to “modernizing” schemes, in the conviction that modernization will deliver improved irrigation performance (Beekman et al., 2014; de Bont et al., 2019; Veldwisch, 2019). Yet, without technology appropriation by farmers (i.e., farmers’ adoption and adaptation of modern technology to their own setting), modernization of farmer-managed irrigation schemes may actually aggravate the problem of excessive sedimentation. This is because farmers’ knowledge about the sedimentation problem may be overlooked and inadequate information and resources/technologies may be available locally for the farmers to undertake operation and maintenance of the system, whereas farmers are the best sources of information and knowledge about their localities (Kolagani et al., 2015; Nigussie et al., 2017; Oliver et al., 2012; Ritzema et al., 2011).

Weak institutions for the management of schemes and poor operation and maintenance practices followed by users are also among the major contributors to the problem of excessive sedimentation (Abate, 2007; Amede, 2015; Awulachew and Ayana, 2011). As excessive sedimentation in irrigation schemes is inevitable, strong institutions for scheme operation and maintenance can play a crucial role in reducing the problem. To craft strong institutions for appropriate management of excessive sedimentation, it is essential that local values, norms, and knowledge be considered, as well as the diversity of irrigators, while also ensuring participation of and consultation with all the concerned stakeholders (Dessie et al., 2011; Fraser et al., 2006; Veldwisch, 2019; Yami, 2013). This is particularly so in a country like Ethiopia, where social capital is rooted in local groupings organized around religious, burial, and wedding ceremonies, community savings, and loan services. Such local associations serve as platforms for communication and conflict resolution, which are also highly valuable for the sustainable management of irrigation schemes (Yami, 2016). For instance, farmers value the “traditional or informal” conflict resolution mechanism higher than the “formal” legal system. Often, they discuss issues of scheme management on indigenous social gatherings, such as wedding or burial ceremonies.

Despite the foremost role of local norms, values, and knowledge, as well as institutions and stakeholders, in managing excessive sedimentation in irrigation schemes, few studies address these aspects directly. Most research rather investigates sediment transport, focusing essentially on understanding sedimentation processes and modeling sediment transport (Depeweg and Mendez, 2007; Depeweg and Méndez, 2002; Depeweg et al., 2016; Munir, 2011; Osman, 2015; Paudel, 2010; Theol et al., 2019a; Timilsina, 2005). Improved operation and maintenance of the system and real and coordinated participation of concerned stakeholders are crucial in dealing with excessive sedimentation problems. The current study therefore looks at stakeholder perceptions of the problem of excessive sedimentation and their roles in its management. We applied a collaborative and participatory approach to analyze sedimentation management practices in two irrigation schemes in Ethiopia. The results of the analysis are presented, followed by a discussion of the influence of institutions and scheme modernization.

2.2 Materials and Methods

2.2.1 Study Area

2.2.1.1 Location and Description of the Study Area

Two irrigation schemes in Oromia Regional State in the Great Rift Valley Basin of central Ethiopia, an area seriously affected by land degradation and erosion, were selected: Ketar medium-scale irrigation scheme and the Arata-Chufa small-scale irrigation scheme (Figure 2.3). The main reason to select these schemes was that farmers manage to keep the irrigation system in good working order despite the excessive sedimentation problems.

In addition, the following criteria were applied in selecting the case study sites: (i) the scheme should be a gravity/diversion type, making use of river runoff; (ii) the scheme of interest should utilize a river as its water source; (iii) the scheme should be managed exclusively by farmers or an irrigation community; (iv) the users should have a relatively long period of experience in water and sediment management; (iv) the scheme should be functional for a relatively long period; (vi) management of the scheme should face relatively severe sedimentation problems; and (vii) a water user association (WUA) should be active in scheme operation and management.

Ketar is medium-scale irrigation scheme, located at 7°49 N and 39°02 E, covering 430 ha, with an average elevation of 2294 m above mean sea level. Having a total main canal length of 12.1 km, the scheme consists of three sections: Ketar 1 (Ketar Genet), covering 110 ha and providing water to 289 households; Ketar 2 (Ketar Golja), covering 200 ha and providing water to 415 households; and Ketar 3 (Hamsa Gasha), covering 120 ha and providing water to 370 households. Each section has its own independent water users' association (WUA). The scheme is affected by sedimentation problems both from the river and overland flow sources.

Arata-Chufa is small-scale irrigation scheme, located at 7°59 N and 39°02 E, covers 100 ha, with an average elevation of 1740 m above mean sea level. This scheme's two main canals have a total length of 1.19 km, and supply water to 10 irrigation blocks. The water users' association of the scheme is one of the well-organized WUAs in the country. The scheme is mainly affected by sediment from the River sources.

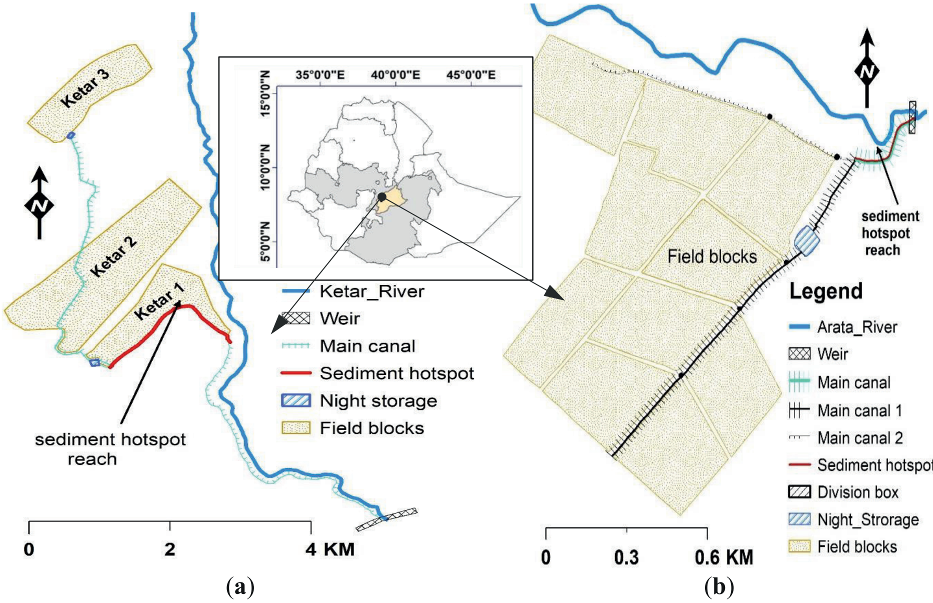

Figure 2.3: Location of the study area with the two case-study irrigation schemes: (a) the Ketar medium-scale irrigation scheme; (b) the Arata-Chufa small-scale irrigation scheme.

2.2.1.2 Climatic Conditions

Rainfall is bimodal in the study region. There is a long rainy season ("Meher") from June to September, a dry season ("Bega") from October to January and a short rainy season ("Belg") from February to May (Table 2.1). Maximum and minimum temperatures at the Ketar scheme are 27 °C and 8.5 °C, respectively. The temperature range is wider at the Arata-Chufa scheme, from a maximum of 35 °C to a minimum of 5 °C. In the Ketar area, mean annual rainfall is 800 mm, and it is 620 mm in the Arata-Chufa scheme vicinity (2012–2016 data). The dry and short rainy periods are the main seasons for irrigated agriculture with mainly cash crops planted. The long rainy period provides the main cropping season for cereals, which are widely planted under rainfed conditions. The dry and short rainy periods are the main seasons for irrigated agriculture with mainly cash crops planted. Cereals are also cultivated to a limited extent in the short rainy period under rainfed condition.

Table 2.1: Mean monthly climatic and cropping data in the study area, from the meteorological stations at Ogolcho (11 km from Arata-Chufa scheme) (2012–2015) and Kulumsa (25 km from Ketar scheme) (2012–2016).

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
Season	**Bega**	**Belg (Light Rain)**				**Meher/Kiremt (Rainy)**				**Bega (Dry)**			
Ogolcho Station													
Rainfall (mm)	0	6	49	48	49	55	160	111	99	45	1	0	621
Temperature (℃)	19	21	22	23	23	23	21	22	21	20	20	18	23
Kulumsa Station													
Rainfall (mm)	3	9	47	55	113	77	150	117	150	67	10	3	801
Temperature (℃)	17	18	20	19	19	19	18	16	17	17	17	16	20
Evaporation (mm) (Average monthly from 2012-2015)	196	193	206	176	159	129	104	92	87	185	151	185	206
Crops	=>	<= vegetables =>				<= cereals =>				<= cereals & veg			
IR[1] or RF[2]	=>	<= irrigation & rainfed =>				<= rainfed =>				<= irrigation			

[1] Irrigation; [2] Rainfed.

2.2.1.3 Irrigated Area and Layout

The Arata-Chufa scheme initially had an irrigated area of 100 ha. Land redistribution activities in 1994/1995 resulted in an average landholding of 0.5 ha (Table 2.2). At the time of this study (October 2016 to August 2017), the irrigated area had expanded to 120 ha, as irrigation had progressively attracted more users. Likewise, for the Ketar scheme, the initially planned area of 110 ha had expanded to 128 ha, also due to increasing demand. Beneficiary numbers had risen in both the Arata-Chufa and Ketar schemes, respectively, from 324 to 374, and from 280 to more than 680.

Table 2.2: Irrigated area and numbers of households of the Ketar and Arata-Chufa irrigation schemes (JICA, 2004); Arata-Chufa and Ketar WUA Office; Personal communication, January 2016).

Ketar	**MC[1] = 2 (1190 m), SC[2] = 8 (3712 m, Division Box = (6), Area Boundary = (10)**										
Subsections	Ketar 1				Ketar 2			Ketar 3			
Area	120				200			110			
Households (no)	289				415			370			
Arata-Chufa	**MC = 2 (1190 m), SC = 8 (3712 m) ,Division Box = (6), Area Boundary = (10)**										
Field block	1	2	3	4	5	6	7	8	9	10	Total
Area (ha)	10.1	9.9	9.9	10.1	9.9	9.9	10.2	9.6	9.9	9.9	100
Households (no)	36	30	32	36	32	30	35	32	31	30	324

[1] main canal; [2] secondary canal.

2.2.1.4 Farming System

The study area is characterized by a traditional livestock-based mixed-farming system, with both crop production and animal husbandry. Predominant rainfed crops are food grains and pulses, including wheat, barley, teff, maize, beans, and haricot beans. Teff, onion, potato, cabbage, carrot, and tomato are the main crops grown under irrigation.

2.2.2 Participatory Rapid Diagnosis and Action Planning Approach

A participatory rapid diagnosis and action planning approach (Lempériere, 2014) was implemented to identify the causes of excessive sedimentation in irrigation schemes, to analyze the perception of stakeholders on the cause of excessive sedimentation problems and their solutions to perceived causes, and to scrutinize how irrigation systems has sustained under excessive sedimentation conditions by the farmers. This consisted of the following steps:

- A literature review of policy documents, such as the Ethiopia Growth and Transformation Plan, irrigation performance reports, and other written materials from government and non-government sources;
- Semi-structured interviews with selected professionals, WUA members, and farmers to understand their roles in managing excessive sedimentation and their perceptions of the drivers of excessive sedimentation, as well as to understand operation and maintenance practices and farmers' involvement in the schemes;
- A participatory rural appraisal (PRA) of both irrigation schemes, including transect walks, resource map, structured direct observation, cropping calendars, and stakeholder analysis.

One hundred semi-structured interviews were conducted with selected professionals, WUA members, and farmers (Table 2.3). Interview subjects were selected based on the location of their farmlands and their roles and responsibilities in scheme management. At Ketar 1, three farmers were interviewed, one from the headrace, one from the middle zone, and one from the tailrace. At Ketar 2 and 3, twelve and eleven farmers, respectively, were selected from the secondary block of each. In each field block of the Arata-Chufa small-scale irrigation scheme, two farmers (one from the headrace and one from the tailrace) were selected for interview. Interviews sought to gather the frequencies of maintenance, including sediment cleaning and responsibilities of the various stakeholders, while also investigating how the farmers dealt with the problem of sedimentation. Respondents were asked how they organized dredging, their views on problems related to sedimentation, factors they thought contributed to the problem, and solutions proposed.

The PRA provided insight into the available resources and opportunities and challenges presented by excessive sedimentation. Component structures of the irrigation schemes were catalogued and sediment hotspots were identified. The strategies employed by the farmers to keep the schemes function were analyzed. The types of crops grown and cropping patterns were also documented, alongside the irrigation technologies available and used. Finally, researchers acquainted themselves with operation and maintenance practices.

Table 2.3: Semi-structured interviews conducted to gain a better understanding of the design, operation, and maintenance of the Ketar and Arata-Chufa irrigation schemes.

Interview Subject Role	Number. of Subjects	Topics Addressed
Government		
- Department head	2	Role in irrigation scheme, perceived causes of and solutions to excessive sedimentation
- Engineer	5	Role in irrigation scheme, perceived causes of and solutions to excessive sedimentation
- Researcher	1	Role in irrigation scheme, perceived causes of and solutions to excessive sedimentation
Ketar 1		
- WUA official	3	Operation and management of irrigation scheme, perceived causes of and solutions to excessive sedimentation
- Gate operator	2	Water distribution and sediment management
- Farmer (3 per block)	30	Role, cause of and solution to excessive sedimentation
Ketar 2		
- WUA official	1	Operation and management of irrigation scheme, perceived causes of and solutions to excessive sedimentation
- Farmer (1 per block)	12	Role, cause of and solution to excessive sedimentation
Ketar 3		
- WUA official	1	Operation and management of irrigation scheme, perceived causes of and solutions to excessive sedimentation
- Farmer (1 per block)	11	Role, cause of and solution to excessive sedimentation
Arata-Chufa		
- WUA official	2	Operation and management of irrigation scheme, perceived causes of and solutions to excessive sedimentation
- Block head	10	Water distribution, role and perception of sediment management
- Farmer (2 per block)	20	Role, cause of and solutions to excessive sedimentation

2.3 Results

2.3.1 Perception of the Drivers for Excessive Sedimentation Problems

2.3.1.1 Upstream, Midstream, and Downstream Farmers

Many of the farmers interviewed at Ketar—upstream (29%), midstream (31%), and downstream (25%)—identified the earthen canal (main canal without a concrete lining) to be a main cause of excessive sedimentation (Figure 2.4). The majority of farmers (60% of upstream farmers) and (69% of midstream farmers) considered faulty design to be a major cause of excessive sedimentation. A small proportion (8%) of the midstream farmers attributed the problem to poor operation and maintenance. The majority of downstream farmers (75%) suggested design problems or faulty design as the main cause of excessive sedimentation, and one fourth (25%)

pointed to external factors as the main driver. None of the interviewed farmers at the downstream scheme (Ketar 3) attributed the problem of excessive sedimentation to poor operation and maintenance practice.

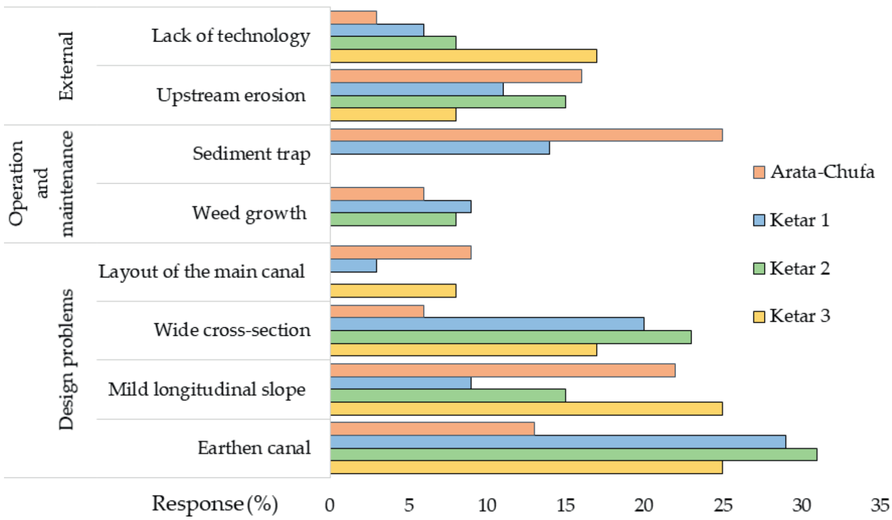

Figure 2.4: Causes of excessive sedimentation in irrigation schemes, according to upstream (Ketar 1), midstream (Ketar 2), downstream (Ketar 3), and Arata-Chufa farmers.

2.3.1.2 Ketar and Arata-Chufa Farmers

The farmers interviewed at the two irrigation schemes reported different perceptions of the causes of excessive sedimentation (Figure 2.4). Foremost driver mentioned by farmers at the Arata-Chufa scheme was an absent and non-functioning sediment trap (25%), while the majority (28%) of the farmers interviewed at the Ketar scheme pointed to the lack of a concrete-lined main canal. This was the fourth most mentioned factor by the farmers at the Arata-Chufa scheme. The minority of respondents at the Ketar scheme (10%) associated the cause of excessive sedimentation with poor operation and maintenance practice. In the Arata-Chufa, a small portion (19%) of the interviewees, unlike Ketar counterparts, reported external factors as a major cause of excessive sedimentation.

2.3.1.3 Farmers and Engineers

Well over half of the respondent farmers (64%) claimed design problems as a major driver of excessive sedimentation problem, while just a few of the interviewed engineers (13%) agreed that design issues were at fault (Figure 2.5, Table 2.4). Nearly two thirds (62%) of the interviewed engineers attributed excessive sedimentation to external factors, particularly erosion of highland areas (37%) and lack of technology and materials (25%). One fourth (25%) of the interviewed engineers claimed poor scheme operation as major driver of excessive sedimentation, while a small portion (21%) of interviewed farmers claimed poor operation and maintenance practice to be a cause of excessive sedimentation problem.

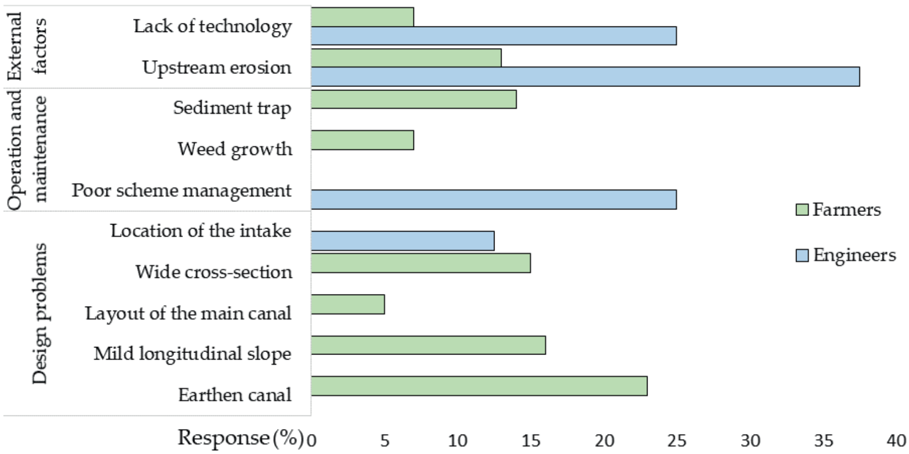

Figure 2.5: Causes of excessive sedimentation in irrigation schemes, as reported by respondent famers and engineers.

Table 2.4: Farmers' and engineers' roles and perceptions on excessive sedimentation in the case-study irrigation schemes.

	Farmers/Water User Associations	Engineers/Government Officials
Causes of excessive sedimentation	▪ Design problems: use of earthen canal, a too mild longitudinal slope, an overly wide cross section and poor layout of the main canal ▪ Poor operation and maintenance: weed growth and dysfunctional sediment trap ▪ External factors: upstream erosion and lack of locally available technology and materials	▪ Design problems: location of the intake ▪ Poor scheme management: poor operation practice of the system by users ▪ External factors: erosion of uphill areas due to land degradation upstream, lack of technology
Solutions proposed	▪ Lining water conveyance structures with concrete ▪ Acquiring machinery for cleaning the sediment ▪ Frequent and timely maintenance of damaged structures	▪ Modernization of the scheme: shifting from surface to pressurized systems ▪ Improving operational practices ▪ Improving design practices ▪ Upstream watershed management activities

This study found that the main way farmers dealt with excessive sedimentation was to mobilize and engage huge amounts of labor (among system users) for intensive sediment cleaning campaigns that were completed within just a few days (3–5 days). Dates for canal cleaning were chosen carefully, considering public holidays and the end of the wet season, to avoid having to repeat the job due to overland flows and backflows of sediment removed from the canal. Despite frequent dredging, farmers also used the technique of delaying water abstraction at the beginning of a new irrigation season (in other words, at the end of every wet season), to avoid entrance of huge amount of sediment together with high sediment content water. The process of delaying water abstraction has potentially reduced the sediment load at the beginning of the irrigation season. This process was managed by the WUAs, which had full autonomy to open and close the intake gate. They have also applied their own techniques for frequent removal of weed grown in the canal cross-section as they believed it traps a significant amount of sediment load.

2.3.2 Days of Labor Invested by Farmers to Manage Excessive Sedimentation

At the Ketar scheme, 3150 and 3086 days of labor were required to dredge 2690 m^3 and 2522 m^3 of sediment from 2433 m (20%) of the main canal (critical sedimentation hotspot) in 2017 and 2018, respectively (Table 2.5). Each farmer removed an average of 0.85 m^3 and 0.81 m^3 sediment per day in 2016/2017 and 2017/2018, respectively. At the Arata-Chufa scheme, 878 and 709 days of labor were required to clean 1845 m^3 and 163 m^3 volume of sediment from 50% of the main canal (600 m) in 2017 and 2018. Each farmer at the Arata-Chufa scheme removed an average of 0.21 m^3 and 0.23 m^3 per day in 2016/2017 and 2017/2018, respectively. Ketar scheme farmers removed 75% and 72% more cubic meter of sediment in a day than Arata-Chufa scheme farmers in 2017 and 2018, respectively.

Table 2.5: Sediment volume removed from the main canal of Arata-Chufa and Ketar and days of labor required.

Scheme	Farmers Involved (Number)	Working Hours (Hrs/Day)	Days Input (Day)	Total Input (Day)	Sediment Removed (m^3)	Output (m^3/Day/ Farmer)	Canal Reach (m)	Sediment Removed (m^3/Day)
Ketar								
- 2016/2017	1680	5	3	3150	2690	0.85	2433	1.11
- 2017/2018	1646	5	3	3086	2522	0.81	2433	1.04
Arata-Chufa								
- 2016/2017	260	4.5	6	878	185	0.21	600	0.31
- 2017/2018	252	4.5	5	709	163	0.23	600	0.27

2.3.3 Time Invested by Farmers in Agriculture and in Cleaning Excessive Sedimentation

Farmers' participation in sediment management varied according to the severity of the sedimentation problem in their particular scheme. The work required to manage excessive sedimentation significantly influenced the labor input to produce a crop (Table 2.6).

Table 2.6: Hours invested by farmers in crop production and sediment cleaning activities to produce onion on 0.25 ha, considering a cropping period of four months (data from farmer interviews).

Irrigation Schemes	Number of Hours Invested by Farmers in Crop Production (hrs)	Percentage of Time Invested by Farmers in Sediment Management (%)
Ketar 1(upstream)	585	23
Ketar 2 (midstream)	497	9
Ketar 3 (downstream)	465	3
Arata-Chufa	513	12

Upstream farmers spent 15% more time on crop production and 65% more time on the management of excessive sedimentation than midstream farmers. Compared to downstream farmers, upstream farmers (Ketar 1) spent 20% more time on crop production and 90% more time managing excessive sedimentation. Midstream farmers spent 6% more time on crop production and 68% more time on excessive sedimentation management, compared to downstream farmers.

Overall, Ketar farmers spent 12% and 53% more time, respectively, on crop production and excessive sediment management than the Arata-Chufa scheme farmers.

2.3.4 Role and Structure of Water Users' Associations (WUAs) in Management of Excessive Sedimentation

WUAs collect annual operation and maintenance fees. In the Ketar scheme, farmers paid an annual US$ 8.73 operation and maintenance fee. If they did not participate in sediment cleaning activities, they were fined US$ 4.36, with this amount increased to US$ 6.55 for a second day of nonparticipation. Of that amount, US$ 2.18 went to the local police, who were delegated to take the legal action. At the Arata-Chufa scheme, member farmers paid an annual operation and maintenance fee of US$ 4.36 (1 US dollar = 22.916 birr (June, 2017)) for 0.25 ha of irrigated land, and they were required to participate in maintenance activities. If they did not participate, they were sanctioned with a US$ 1.75 fine. Farmers who were not WUA members paid US$ 13.09 for access to water.

The WUA structure for the Ketar irrigation scheme was originally introduced by "external actors" upon establishment of the scheme (Figure 2.6). The current organizational set-up has, however, drastically changed; only the functions of WUA head, deputy head, secretary, and cashier existed and the farmers themselves had established the "farmers' collective", which was observed to play an important role in dealing with the problem of excessive sedimentation. This collective implements and manages a major desilting campaign and coordinates minor repair activities. It is made up of subgroups of maximum 20 members. These subgroups are fully autonomous and responsible for imposing sanctions on members who do not participate in sediment cleaning activities.

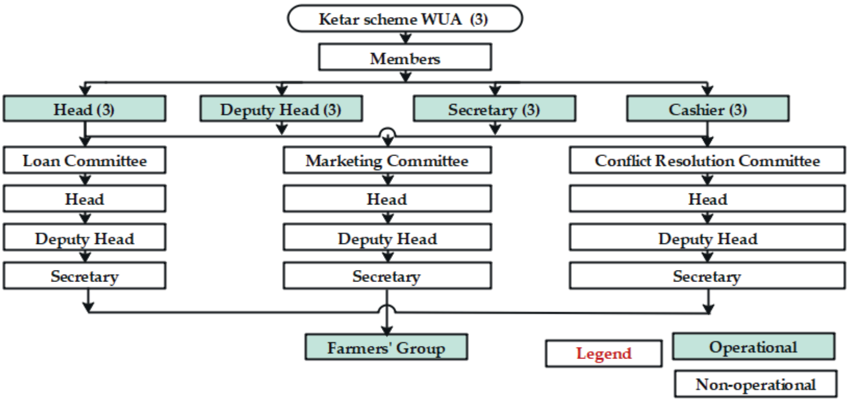

Figure 2.6: Institutional set-up of the water user association (WUA) of the Ketar irrigation scheme (from the interview results).

The institutional set-up of the Arata-Chufa WUA was also established by "external actors" in 1985/1986, at the time the scheme was handed over to the beneficiaries (Figure 2.7). The WUA head, deputy head, secretary, and cashier were observed to still be active and engaged in scheme operation and maintenance. The "field block", though not part of the original structure, had been set up by farmers to monitor the operation and maintenance of each block. As such, the field block heads were the main bodies responsible for monitoring sediment cleaning activities in secondary and tertiary systems and managing water distribution to each field block.

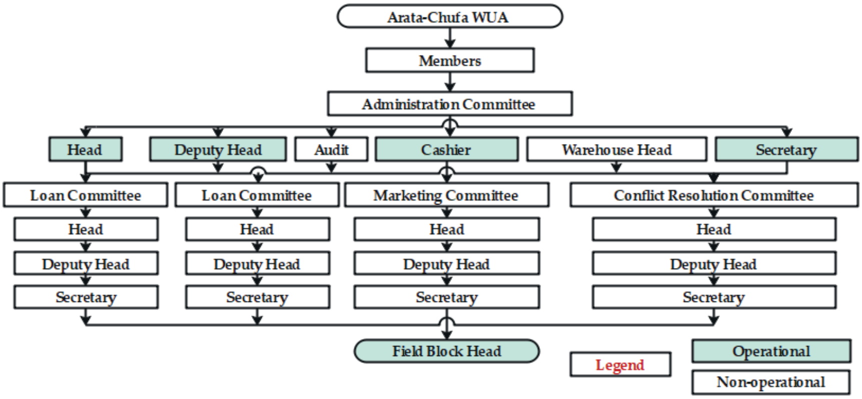

Figure 2.7: Institutional set-up of the water user association (WUA) of the Arata-Chufa irrigation scheme (from the interview results).

2.3.5 Scheme Modernization and Management of Excessive Sedimentation

The annual operation and maintenance fees paid by the farmers were not sufficient for required maintenance or repair cost. Farmers reported undertaking only minor maintenance activities by their own, saying that lack of resources and technology limited their ability to do so (Table 2.7). Due to lack of technology appropriation, farmers depend on "external actors" for major maintenance activities that curtailed their autonomy in keeping excessive sedimentation under control. The dependence of the farmers on external actors for maintenance and repair particularly concern the farmers for two issues. One, they could not afford the maintenance cost of the scheme requested by local contractor. Two, as they file scheme maintenance requests to the lowest Government office, this often took longer to respond to the timely needed repair request of the farmers.

Table 2.7: Scheme component structures and ability of farmers to maintain them autonomously at the Arata-Chufa and Ketar irrigation schemes.

Scheme Component Structures	Maintained by Farmers
Headwork/intake/weir	no
Lined canal	no
Earthen/unlined canal	yes
Division boxes	no
Gates	no
Night storage ponds	no
Sediment cleaning—canal systems	yes
Sediment cleaning—night storage ponds	no
Chute	no
Drop	no
Turnouts/offtakes	no

2.3.6 Opportunity Cost of Scheme Operation and Maintenance

The farmers at the Ketar scheme paid US$ 8.37 annually for operation and maintenance (O&M), whereas Arata-Chufa farmers paid US$ 4.36. O&M fee was based what normally the users have agreed and afford to pay. The opportunity cost incurred by the farmers for their labor to dredge sediment just of 50% and 20% of the main canal length, respectively, for the Arata-Chufa and Ketar scheme were US$ 3457 and US$ 13,594, respectively. This means that if the farmers should be paid from annual O&M fees to cover for cleaning of excessive sedimentation from the canal and did not contribute labor, the WUAs would encounter a budget deficit of 145% and 45% for the Arata-Chufa and Ketar scheme, respectively (Table 2.8).

Table 2.8: Average annual maintenance opportunity cost incurred by water user association (WUA) members and actual cost to clean sediment from the main canal systems.

Water User Association (WUA)	Members (Farmers)	Operation and Maintenance Fee (US$/Year)	Total Operation and Maintenance Fees Paid (US$/Year)	Average Time Spent on Desilting (Days/Year)	Labor Cost Per Day (US$)	Estimated Maintenance Opportunity Cost (US$)
Arata-Chufa	324	4.36	1413	793	4.36	3457
Ketar	1074	8.73	9376	3118	4.36	13,594

2.4 Discussion

A few key differences were found in the perceptions of the farmers on the sedimentation problems. The difference in views reflects the farmers' awareness of the problems they were facing. For instance, the foremost mentioned driver by the farmers interviewed at the Ketar scheme was the lack of a concrete-lined main canal, while the majority of respondents at the Arata-Chufa scheme pointed to an absent and non-functioning sediment trap. This difference in views can be attributed to the fact that the main canal of the Arata-Chufa scheme was already lined with concrete at the most critical sediment hotspot, whereas it was still earthen at the Ketar scheme. The cross-section (width and depth) of the main canal was the other most reported cause of excessive sedimentation problem by the farmers at the Ketar scheme. The farmers mainly concerned with the cross-section of the main canal at the critical sedimentation sections. This is because the cross-section determines the quantity of sediment cleaned by the farmers. They remove the deposited sediment from the canal bed and weeds from the side banks of the canal at the same time. In doing so, they further dig the bed of the canal and trim the side banks of the canal. This combined activity results in a damaged canal cross-section: deeper, wider, and a changed longitudinal slope of the canal. The maximum width and depth of canal at the sediment hot spot were recorded as 3.2 m and 0.85 m. Though this was not too wide, it was difficult for the farmers to remove the sediment from such cross-section by manual labor only.

The other reasons mentioned by the farmers as the causes excessive sedimentation that related to their acute awareness of their specific scheme were; absence and non-functional sediment trap, source of erosion, and longitudinal slope of the main canal. The Ketar upstream and Arata-Chufa farmers emphasized the importance of having a working sediment trap. Ketar 1 and Arata-Chufa schemes were initially equipped with sediment trap and undersluice gate that serve to flush sediment back into the river, which was non-functional during interview period. The farmers indicated that with timely repair and improved operation of the sediment trap and undersluice gate, the problem of excessive sedimentation could be substantially reduced. This is because they had previous experience with the function of fully operational structures. With regard to sources of erosion, farmers at the Arata-Chufa scheme reported erosion outside the scheme as a major factor aggravating sedimentation problems. Here they referred to farmers who used pumps to irrigate in a buffer zone of the river just upstream of the intake for causing much of sedimentation problems in their scheme. Ketar farmers, however, attributed excessive sedimentation to erosion of agricultural lands within the scheme. Contrary to other farmers, farmers at the Ketar 3 mainly identified gentle longitudinal slope as a cause of excessive sedimentation problems. This is due to the fact that most reaches of the main canal from Ketar 2 to Ketar 3 was laid in chute structure, which is not suitable condition either for the sediment to settle or for the growth of weed. None of the downstream farmers though mentioned weed growth in the canal as a major cause of sedimentation problem

It is not surprising that engineers had somewhat different perceptions of excessive sedimentation than farmers. While farmers saw structural, technical, and external factors as the main drivers of excessive sedimentation, engineers attributed excessive sedimentation mainly to poor scheme operation and maintenance, as well as erosion of upstream areas. One design problem that engineers did note was the location of the intake, though the design issues cited by farmers related to the layout of the main canal (slope, cross-section, lining materials). With respect to technology, the engineers emphasized the potential of moving away from surface irrigation towards pressurized irrigation technologies (sprinklers and drip) as an option to address excessive sedimentation, while farmers demanded technologies for removing the sediment from the canal and night storage ponds and conveying irrigation water. In sum, most of the drivers of excessive sedimentation reported by farmers (too mild longitudinal slope, wide and shallow canals, absence of and dysfunctional sediment trap) were indeed consequences of poor design and operation and maintenance of the schemes. In this regard, the findings of the current study confirm evidence from previous work (Abate, 2007; Amede, 2015; Awulachew and Ayana, 2011). For instance, the longitudinal slope of the main canal at the sediment hotspot was calculated as 2.3‰ for the Arata-Chufa scheme and 1.4‰ for the Ketar scheme. This can be regarded as a very gentle slope, confirming farmers' claims. This sediment hotspot reach of the canal with very gentle slope reduces flow velocity and allows the sediment to settle. Designing for an optimum permissible velocity that neither allows sediment to deposit nor scours the canal bed could improve sediment transport in the canals.

At the Ketar scheme, the main sediment hotspot section was found at the upstream scheme (Ketar 1) 5 kilometres from the intake (Figure 2.3). This section covers 2433 m (20% of the main canal). The main canal is collectively cleaned mostly once, but sometimes twice a year depending on sediment inflow load. The secondary and tertiary canals, which are adjacent to the field plots, were cleaned by the farmers individually. The work load of sediment management differed between the upstream, midstream and downstream farmers due to the difference in sediment inflow load (Table 2.6). The majority of the sediment settled at the upstream (Ketar 1) scheme. Thus, upstream farmers spent more time on sediment management compared to midstream and downstream farmers. Furthermore, downstream farmers were least affected by the sedimentation problem, and contributed the fewest hours of labor to cleaning sediment as they irrigate with water stored at night storage pond. This reveals that the management of excessive sedimentation brings other issues to the fore regarding interactions between upstream, midstream and downstream farmers. Previous studies (Amede, 2015; Bijani and Hayati, 2015; Ravnborg et al., 2012) argue that upstream farmers may have a comparative advantage over midstream and downstream farmers in terms of water availability; that is, more water may be available to upstream users, with less flowing to the middle and downstream zones. We point out, however, that this is not always the case. The current case study suggests that middle-stream and downstream farmers had similar water allocations to upstream farmers, but invested less time in management of excessive sedimentation.

The role of the WUAs in relation to sediment management tasks were to set the annual sediment cleaning and maintenance dates, monitor sediment cleaning activities, and communicate with the local government bureau to file requests for scheme maintenance and repairs that the farmers could not perform on their own. WUAs also play the role of enforcing the sanction that was set out in the WUA by-laws. However, it was found that these rules were hardly applied. For instance, in the Arata-Chufa scheme, the fines farmers paid depended on crop yields and market values in a particular year. If productivity was high, the sanction to be paid by offending farmers was increased; otherwise, it would be reduced. By-laws stipulating that farmers would not get water if they did not participate in maintenance were also softened, in particular, for women and elderly farmers or at least excused from participation in the heavy work of desilting. At the Ketar scheme, farmers followed their own rules for sediment cleaning. The farmers' group (formed by the farmers themselves) decided collectively what type and magnitude of sanctions to impose on those who did not participate. It was observed that there was relatively good communication and consensus within the groups, which made it easy for farmers to empathize with the situation of those who had not participated in cleaning activities. If the reason for not participating was deemed acceptable, the farmer was excused; if not, an appropriate sanction either in kind or in cash was imposed and the farmer generally paid it. Thus, local norms, values, and social capital seem to have played a substantial role in keeping these schemes functional for more than 30 years. Functions introduced by the "external actors", such as audit, loan, marketing, conflict resolution, and warehouse, were inactive. Instead farmers themselves formed positions like "farmers' group" "field block head". Farmers consider roles that still exists such as head, deputy head and secretary as "traditional role".

The majority of farmers were willing to pay the annual operation and maintenance fee, to contribute labor to clean the sediment, and to pay sanctions if required. Moreover, they considered the annual operation and maintenance fee to be fair. There were, however, various scheme components that the farmers could not maintain and repair on their own, mainly due to the modernization of the schemes. While farmers could do minor repairs of earthen canal works and dredge sediment from the main canal, they could not remove sediment from the night storage ponds. In 2016/2017, Ketar scheme farmers paid a local contactor US$ 13,090 to use heavy machinery to excavate the sediment from the night storage pond. At the time of the field work, Arata-Chufa scheme farmers were facing a shortage of water because they lacked the machinery and funds to pay for sediment to be cleaned from the night storage pond, which supplied 60 ha, or 60%, of the total irrigated area. This reflects the problem of a lack of technology appropriation, which studies have shown leaves users dependent on external technology and developers (de Bont et al., 2019; Veldwisch, 2019). Farmers were willing to invest, and of course they annually contributed a huge amount of labor to manage excessive sedimentation, but the operation and maintenance fees paid were insufficient to cover major maintenance and repair costs.

The labor output in the Ketar scheme was higher than the Arata-Chufa scheme (Table 2.5). This difference could be attributed to the work processes implemented to manage the desilting activities at the different schemes. The Ketar scheme had a better system, which was more effective in utilization of the labor days invested by the farmers. Farmers were divided into groups numbering a maximum of 20 each. The desilting operation was then divided among the groups, with every 20 farmers responsible for about 100 m of the canal. At the Arata-Chufa scheme, sediment cleaning was carried out collectively in a process in which only a few farmers could be actively engaged in dredging at a time, while the remaining farmers stood aside and waited for their turn. It is very difficult to compare the labor output at the two schemes to experiences elsewhere in the country, as very little data exists on the quantity of sediment desilted by farmers from canals and numbers of labor days devoted to the task. However, we estimated the opportunity cost of those labor days as US$ 3457 and US$ 13,594 for the Arata-Chufa and Ketar schemes, respectively. Comparing these estimates to the total regional operation and maintenance budget for 2017/2018 ($1.2 million), we found that 0.28% and 1.11% of the regional budget would be spent to remove sediment from 50% and 20% of the main canals of the Arata-Chufa scheme and Ketar scheme, respectively. The region had 612 modern, 9379 traditional, and 63,523 pump irrigation schemes in that year (OIDA, 2016).

2.5 Conclusions

Excessive sedimentation is indeed one of the major causes of underperformance of small-scale irrigation schemes in Ethiopia. In this study, the stakeholders' roles and perspectives on sedimentation management in two small-scale irrigation schemes, Ketar (430 ha) and Arata-Chufa (120 ha), were analyzed using a collaborative and participatory approach. In these farmer-led irrigation schemes, farmers use their local knowledge and informal institutions to mobilize and engage huge amounts of labor for intensive sediment cleaning campaigns. In the Ketar Scheme, the farmers (1680 in 2016/2017 and 1646 in 2017/2018, respectively) spent on average 3 days per year on this campaign and the farmers in Arata-Chufa (260 in 2016/2017 and 252 in 2017/2018, respectively) on average 5.5 days per year. The upstream farmers spent between 12% (Arata-Chufa) and 23% (Ketar 1) of the total time invested in crop production on sedimentation management, compared to only 3 to 9% of the midstream and downstream farmers. On top of this input in labor, farmers pay annual operation and maintenance fees, US$ 8.37 in Ketar and US$ 4.36 in Arata-Chufa. In these farmer-led irrigation systems, the farmers mainly devoted extra hour of drudgery for desilting excessive sedimentation from the canal, but they have also used their knowledge, such as delaying the abstraction of irrigation water at the start of new irrigation season (end of wet season) to avoid entrance of excessive sedimentation to their scheme together with diluted irrigation water. They have also applied own technique of frequent removal of weed grown in the canal cross-section as they believed it traps a significant amount of sediment load.

Farmers’ understanding of the drivers of excessive sedimentation reflected their close personal knowledge of the irrigation system and the sedimentation problems they faced. Farmers and engineers have different perceptions of the causes of sedimentation. The drivers of excessive sedimentation were indeed the consequences of poor or faulty design, poor operation, and maintenance practices and external factors like erosion due to degradation of the land and low-technology level of water conveyance systems. Farmers reported design problems as the main cause of excessive sedimentation (64%), followed by poor operation and maintenance (O&M) practices (21%), and external factors (15%). Contrary, the engineers indicated erosion and irrigation-technologies as the main causes of excessive sedimentation (62%) and only 13% on design problems. Though low-technology level contributed to the excessive sedimentation problem, lack of adaptation and adoption of the technology by the farmers have aggravated the problem

The existing role and structure of the Water Users Associations are significantly simplified compared to the institutional set-up introduced by external actors, as most of the planned management layers and committees were not operational. Local social capital appeared to be more important than by-laws in enforcing O&M practices. It can be concluded that the cost of sediment management for the farmers is very high and requires new socio-technical solutions that capitalize on the existing local social capital, norms, values, and indigenous knowledge. The integration of the farmers' knowledge with that of the engineers could yield more effective ways to deal with sedimentation problems. To implement a sustainable intervention to rehabilitate excessive sedimentation problems in farmer-led irrigation systems, it should follow a proper technology appropriation by the farmers.

3

Chapter 3

Sedimentation in Small-Scale Irrigation Schemes in Ethiopia: Its Sources and Management

This chapter is based on:
Gurmu, Z. A., Ritzema, H., de Fraiture, C., & Ayana, M. (2022).
Sedimentation in small-scale irrigation schemes in Ethiopia:
Its sources and management.
International Journal of Sediment Research.
doi:10.1016/j.ijsrc.2022.02.006

3. Sedimentation in Small-Scale Irrigation Schemes in Ethiopia: Its Sources and Management[2]

Abstract

Numerous irrigation schemes in sub-Saharan Africa (SSA) exhibit excessive sedimentation, resulting in underperformance and high maintenance costs. In the current study, a participatory monitoring program was used to investigate sediment causes and sources, measure the annual sediment load, and monitor desilting campaigns in two small scale irrigation schemes in Ethiopia, Arata-Chufa (100 ha) and Ketar (430 ha), for three years (2016-2018). Sedimentation quantities were huge; where the annual river sediment influx ranged from 220 m3 for the Arata-Chufa scheme to 1741 m3 for the Ketar scheme. On average 0.3 m3/m of sediment were removed from the main canal for Arata-Chufa costing 794 days of labor per year. In Ketar, sediment quantities were even greater: 1.1 m3/m was removed requiring 3118 days of labor per year. The sediment influx from the river source amounts to up to 95% for Arata-Chufa and moderately reaches 46% for Ketar, with the remainder of the sediment entering with overland erosion flows. Farmers reported increased sedimentation over time and difficulty paying operation and maintenance fees instead preferring to contribute labor for the desilting campaigns. Sedimentation management is fragile and mainly involves frequent desilting campaigns and unharmonized efforts to reduce overland sediment inflows. Factors contributing to sediment deposition include mild longitudinal bed slopes, the location of the intake, canal layout, and lack of canal banks for protection against surface water inflow in addition to sub-optimal canal operations. Excessive sedimentation is a major challenge resulting in underperformance of numerous irrigation schemes in SSA, and the stakeholders' lack of awareness of the sources of sedimentation is an underlying factor aggravating sedimentation problems. It is concluded that investigating the sources, extent, and types of sedimentation entering a small-scale irrigation scheme is the basis for reducing maintenance costs and for effective management of sedimentation problems.

Keywords: Sediment sources; Sediment management; Irrigation performance; Soil loss; River sediment; Erosion

[2] This chapter is based on: Gurmu, Z. A., Ritzema, H., de Fraiture, C., & Ayana, M. (2022). Sedimentation in small-scale irrigation schemes in Ethiopia: Its sources and management. *International Journal of Sediment Research*. doi:10.1016/j.ijsrc.2022.02.006

3.1 Introduction

Sub-Saharan Africa (SSA) is the only part of the world where per capita agricultural productivity did not increase over the past 40 years (Onyutha, 2018; Sanchez and Swaminathan, 2005). The region also has the highest prevalence of hunger, which affected 20.8 million people in 2015 (FAO, 2017b). A key strategy to increase food security and eradicate poverty is raising investment in agricultural production (Ararso et al., 2009; de Fraiture et al., 2010). To achieve the goal of food security since the 1960s, African governments, with the help of international donors, have prioritized development of irrigated agriculture, especially small-scale irrigation (SSI) projects (Bjornlund et al., 2020a; Lam and Ostrom, 2010; Parry et al., 2020). In Ethiopia, international donors have actively supported development of SSI infrastructure since the 1990s (IFAD, 2017). The Government of Ethiopia, too, has pursued agriculture-led economic growth, particularly through expansion of irrigated agriculture. The country's five-year Growth and Transformation Plan (GTP) II foresees a 43% increase in irrigated agriculture between 2016 and 2020 (NPC, 2016).

The outcomes of SSI investments in sub-Saharan Africa, and in Ethiopia, have been far below expectations (Yami, 2016). Many SSI projects have failed due to the underperformance of the irrigation systems (Amede, 2015; Makombe et al., 2001; Yami, 2016). Mutambara et al. (2016) claimed there were no tangible cases of successful and sustainable smallholder and farmer-managed irrigation systems in all of Africa. Indeed, most irrigation systems in Africa operate at less than 50% efficiency, meaning that the expected benefits of the investments seldom materialize (Mwendera and Chilonda, 2013; Pittock et al., 2020). Underperformance due to deterioration of physical infrastructure is explained in part by an overemphasis on system construction in funds allocation, with a comparative neglect of funding for operation and maintenance (O&M). The assumption made by donors and governments is that farmers will handle O&M costs, leading to a lack of the necessary O&M funds (Huppert et al., 2003; Ward et al., 2013). Faulty design, administrative obstacles and environmental problems are other factors resulting in the underperformance of irrigation systems (Abate, 2007; Abebe et al., 2020; Aberra, 2004; Amede, 2015; Awulachew and Ayana, 2011; Bjornlund et al., 2020a). In the past two decades, against a backdrop of diminishing freshwater and land resources, coupled with the acknowledged underperformance of the existing irrigation systems mainly due to severe sedimentation problems from erosion in the upland catchment, the global emphasis has shifted from expansion of irrigated agriculture to revitalization of existing irrigation systems, particularly rehabilitation of infrastructure and improving O&M issues (FAO, 2003).

Excessive sedimentation in water resources systems is critical global problem (Alavinia et al., 2019; Tadesse and Dai, 2019). In irrigation systems it exacts a high cost in terms of water stress (Namsai et al., 2020), unfair water distribution, and complete system failure. Besides altering operations and maintenance, which is key to sustaining irrigated agriculture, it causes system inequity and unforeseen reduction in irrigable area (Lawrence and Atkinson, 1998) where irrigation systems are actually under pressure from global water scarcity. Monetarily, the cost also is high. An annual desilting campaign for a medium-scale irrigation scheme (~430 ha) with a serious sedimentation problem costs US $14,000 and requires the equivalent of 3,100 days of labor (Gurmu et al., 2019). In farmer-managed irrigation systems, clearing sediment deposits brings extra work on top of routine agricultural activities. Moreover, this extra work can undermine social cohesion due to conflicts or sanctions that may arise from failure to participate in annual or seasonal desilting campaigns. Gurmu et al. (2019) found that in irrigation schemes with excessive sedimentation, farmers devoted almost one fourth of their crop production time to sediment management. However, due to the dynamics of irrigation schemes and high uncertainties associated with sediment transport, the farmers were unable to apply better sediment management option.

Sedimentation in irrigation systems broadly comes from two sources: (i) river sediment brought in with the irrigation water via intake structures and (ii) sedimentation brought into the canal networks by on site overland runoff during rain storms. Here, ‘overland flow’ refers to sediment yield from an area/catchment found downstream of an intake/diversion structure that enters an irrigation scheme at any point along a main canal. ‘River sediment’ refers to the part of sediment influx into an irrigation scheme via intake structures with abstracted irrigation water. One or both of these sources may be in play for any specific irrigation system. Sedimentation from river water can be reduced by improved design and O&M practices, but it is not feasible to prevent it entirely, as rivers in Ethiopia carry huge quantities of sediment throughout the year. To reduce sedimentation, farmers might delay abstraction of irrigation water to avoid times when the river’s sediment load is high (Gurmu et al., 2019). Sedimentation from overland flows is a problem particularly when canal banks are too low to act as an effective barrier to overland flow carrying eroded soil from the upland catchment or when surface runoff is not diverted back to the river. Soil erosion from the catchment upland of the main canal is the in-situ source of sedimentation in numerous irrigation schemes. Nonetheless soil erosion due to land degradation is the primary source of sedimentation in water resources (irrigation) systems. Many irrigation schemes can only be threatened by on site soil erosion and sediment yield during wet seasons. Due to the dynamic nature of irrigation schemes that involve complex hydro-social settings, vast topographic and land use variabilities, high uncertainties in water and sediment inflows, and multiple variables, the management of sedimentation problems varies depending on irrigation system under consideration.

Knowledge of the sources, extent, and types of sediment entering an irrigation system is paramount for effective management and infrastructure sustainability (Vellinga, 2004). Though many studies (Bjornlund et al., 2020a; Pittock et al., 2020; van Rooyen et al., 2017) overlook sedimentation as a major cause of poor irrigation system performance, a few other studies (Abate, 2007; Amede, 2015; Awulachew and Ayana, 2011) demonstrate the role of sedimentation in irrigation scheme underperformance. However, information is lacking on sources and quantities of sediment and sediment management practices. The current study used a participatory approach and investigated sediment sources, measured the annual sediment load, analyzed sedimentation causes, and assessed farmer-organized desilting campaigns for two irrigation schemes in Ethiopia to assess the role of sedimentation problems on the performance of small-scale irrigation schemes.

3.2 Materials and Methods

3.2.1 Study Area

The current study focused on the Arata-Chufa and Ketar irrigation schemes, both in the Great Rift Valley Basin of Ethiopia (Figure 3.1). Arata-Chufa, is a 100 ha SSI scheme located at 7^0 59' N and 39^0 02' E, with an average elevation of 1,740 m above mean sea level. The scheme was built as an upgrade of an established system whereby farmers used traditional diversion structures to divert river water for irrigation of some 10 ha of land. The traditional diversion structures were built using stones and trees, but these often were washed away during periods of high river discharge. Responding to a request from some 130 farmers, the Ethiopian government constructed a permanent 42 m masonry weir, which at the time of this study provided irrigation water to 324 households. Arata-Chufa's water user association (WUA) was characterized as one of the best organized in the country.

Ketar is a medium-scale irrigation (MSI) scheme, located at 7^o 49' N and 39^o 02' E and covering 430 ha, with an average elevation of 2,294 m above mean sea level. The scheme was constructed in three sections: Ketar 1 (Ketar Genet), covering 110 ha and providing water to 289 households; Ketar 2 (Ketar Golja), covering 200 ha and providing water to 415 households; and Ketar 3 (Hamsa Gasha), covering 120 ha and providing water to 370 households. Each section had its own WUA. As its construction dated from the mid-1980s, in response to the 1984 drought, the infrastructure exhibited substantial physical deterioration. To reduce seepage losses from the main canal and increase water use efficiency, rehabilitation works were undertaken in 2003-2004 by the Oromia Irrigation Development Authority (OIDA) and local irrigation users, with support from the Japan International Cooperation Agency (JICA). This study looked at the section up to Ketar 1, some 5 km from the intake. This is where the worse sediment hotspots were found.

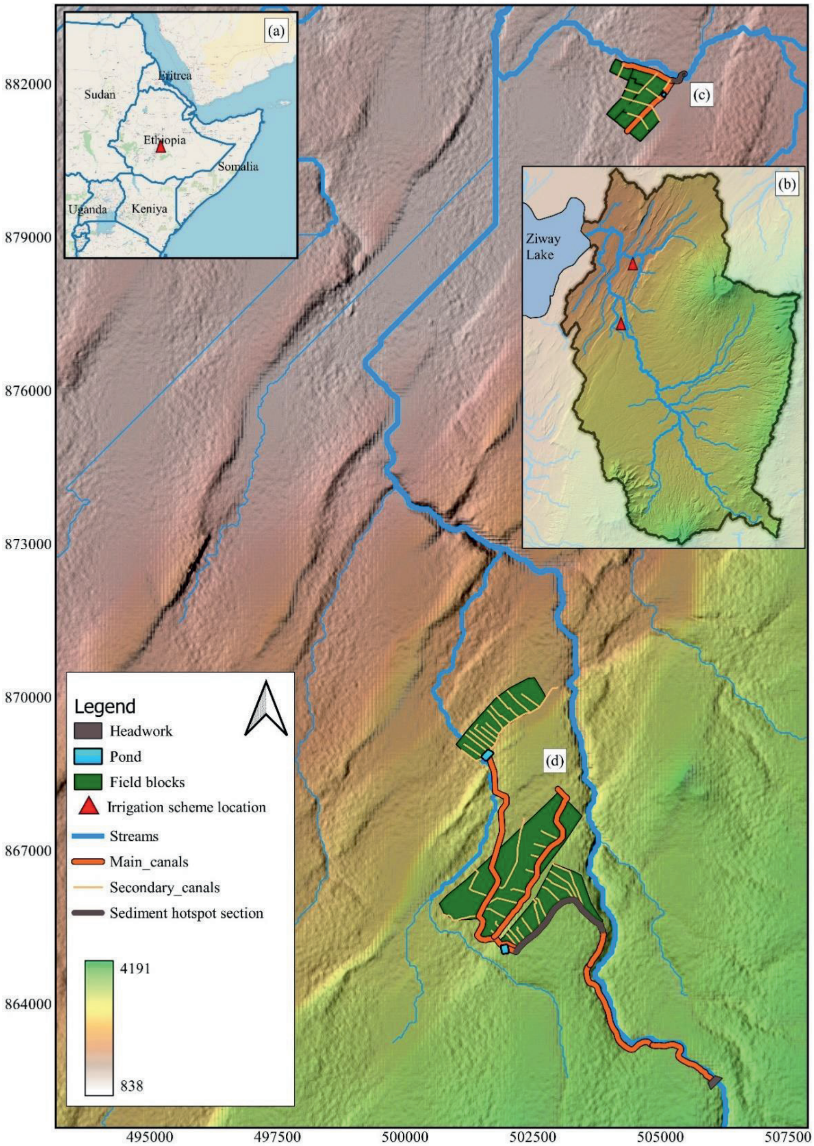

Figure 3.1: Location and layout map of the study areas. (a) Location of the irrigation scheme in Ethiopia. (b) Location of the irrigation schemes in the Ketar catchment draining to Lake Ziway. (c) Lay out of the Arata-Chufa small scale irrigation scheme (100 ha) at the downstream reach of the Ketar catchment withdrawing irrigation water from the Chufa River, a tributary of the Ketar River. (d) Lay out of the Ketar medium scale irrigation scheme (430 ha) upstream from the Arata-Chufa scheme withdrawing irrigation water from the Ketar River.

3.2.2 Methodology

Environmental and resource planning and intervention require reliable data, which many developing countries lack (Gunatilake and Vieth, 2000). Moreover, budget constraints make extensive data collection impractical in countries such as Ethiopia (World Bank, 2008b). To overcome shortcomings of long-term data, various studies have utilized participatory learning and action (Debolini et al., 2013; Gunatilake and Vieth, 2000; Kolagani et al., 2015; Koskinen et al., 2019; Ritzema et al., 2010; 2011). Apart from providing a source of needed data, public participation in research and development activities has been found to have numerous benefits, such as enhancing bottom-up approaches (Al-Qubatee et al., 2017; de Meo et al., 2013); enabling sustainable monitoring of complex and uncertain environmental resources while reducing monitoring costs (Giordano et al., 2010; 2013); supporting flexible, transparent, and higher quality decision-making (Drazkiewicz et al., 2015; Oliver et al., 2012; Reed, 2008); and providing a simple and practical collaboration method that can be tailored to local settings (Kolagani et al., 2015; Yohannes et al., 2019).

The current study applied participatory learning and action (Goss, 2004; Lempériere, 2014) to measure and identify sources of sediment in combination with soil erosion modeling using the Revised Universal Soil Loss Equation (RUSLE) (Wischmeier and Smith, 1978). There were three aims: (i) to measure the sediment load and identify its sources for the two selected irrigation schemes; (ii) to understand and assess desilting campaigns; and (iii) to quantify soil losses and sediment yield to the schemes from the catchment area upland from the main canals. Table 3.1 lists the participatory approach applied in measuring and mapping soil losses and sedimentation for the two schemes. The approach actively engaged local farmers and stakeholders in a joint process of identifying and discussing the sedimentation challenges arising for the two schemes. Participatory learning and action served to acquaint researchers with local practices and the difficulties farmers faced in sedimentation management while also overcoming the scarcity of data to guide interventions to address sedimentation issues.

Figure 3.2 shows the technical flowchart of the participatory monitoring program applied in the current study to investigate the extent, sources, and management of sedimentation for the two irrigation schemes.

Table 3.1: The participatory learning and action approach implemented in the current study.

Study phase	Stakeholders involved	Purpose of study phase	Period
Preliminary survey	– Engineers – Officials – Farmers – Water user associations (WUAs)	Identify sediment hotspots Develop a layout and longitudinal profile of the irrigation schemes	November 2016 to September 2017
Participatory monitoring program	– Farmers – WUAs	Measure the quantity of sediment Examine desilting practices	January 2017 to January 2018
Interviews	– Engineers – Officials – Farmers – WUAs	Assess operation and maintenance practices Assess trends, sources and causes of sedimentation problems	October 2016 to August 2017
Modeling		Quantify soil losses and sediment yield to the canal from overland flow	June 2019 to December 2019

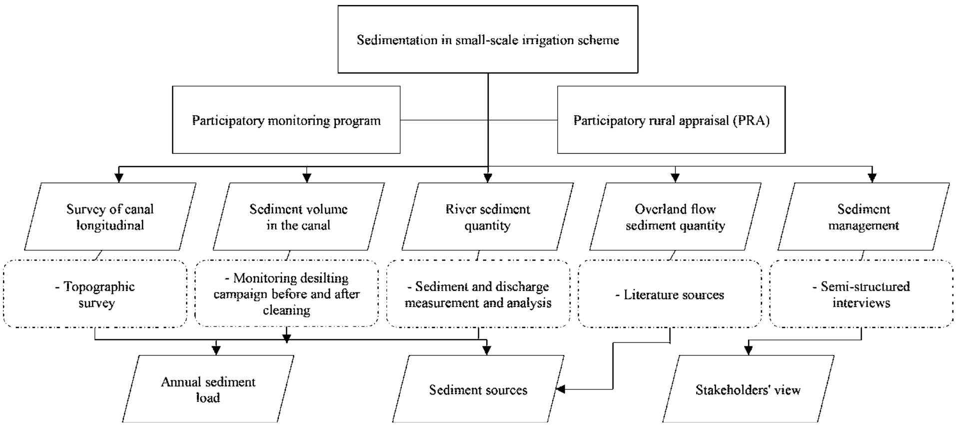

Figure 3.2: Conceptual framework of the participatory monitoring program applied to investigate the extent, sources, and management of sedimentation for the small scale irrigation schemes

3.2.3 Project Phases

3.2.3.1 Preliminary Survey

The project began with a preliminary survey and site selection. The main office of the Oromia Irrigation Development Authority (OIDA), the OIDA East Shoa and Arsi zonal branches, and the Tiyo Woreda Agricultural Office were contacted to learn which irrigation systems were experiencing excessive sedimentation. In choosing the sites to study, consideration also was given to the availability of operational WUAs and farmer groups, farmers' tacit knowledge about sediment management, the specific excessive sedimentation problems faced, opinions of experts and engineers, farmers' willingness to collaborate, and the accessibility of the potential field sites.

After identifying Arata-Chufa and Ketar as potential study sites, an initial field visit was done under the guidance of engineers from the OIDA Arsi zonal branch. During the excursion, meeting with local farmers and WUAs were held to discuss the purpose of the visit and objectives of the research. The researchers also sought to understand what the farmers and WUAs might expect from the research and their willingness to take part. Afterwards, a transect walk was done with WUA leaders and farmers to get acquainted with sediment hotspots in the canal and to learn about desilting practices and activities. The researchers particularly looked at erosion hotspots and at gullies that transported sediment to the main canal.

Because original design documents and working drawings were not available for the selected schemes, topographic surveys were done for both sites, covering 1.3 km for Arata-Chufa and 12.2 km for Ketar. These surveys were done from 28 August to 6 September 2017 using a total station. As such, longitudinal canal profiles were developed and the layout of the schemes was charted to analyze canal bed slope and the effect of layout and bed slope on flow velocity, which influences sediment transport in the canal.

3.2.3.2 Participatory Monitoring

The second project phase was participatory monitoring of desilting campaigns at the selected study sites with participatory field data collection. During desilting campaigns farmers dredge sediment and undertake minor maintenance on the main canal. These activities were undertaken for three to five days in late August and early September. WUA leaders and local farmers participated in counting and recording the number of farmers participating and hours worked daily, while also measuring the volume of sediment cleaned. Discharge and sediment were measured weekly during periods of high sediment inflow and fortnightly when sediment loads were lighter. A current meter and Parshall flume were used to measure canal discharges. DH-48 and BLH-84 sediment samplers were used, respectively, to measure suspended and bedload sediment in addition to bed material grab sampling. The volume of sediment cleaned from the canal by the farmers in the year prior to the field work (2016) was approximated from flood and sediment marks on the canal walls, with the support of local farmers and WUA leaders. Particle size analysis of sediment collected from the canals were done using sieve analysis and the hydrometer method to identify the sources and the types of the sediment in the schemes.

3.2.3.3 Interviews

Semi-structured interviews were done with 100 subjects, including farmers, WUA leaders, and engineers. Questions were asked about sources of sedimentation, trends in sedimentation problems, local sediment management practices, and frequency of desilting campaigns. For a detailed analysis of these interviews, see Gurmu et al. (2019).

3.2.3.4 Sediment Yield from Overland Flow

To model the quantity of sediment lost and delivered to the main canal from overland flow sources, the Revised Universal Soil Loss Equation (RUSLE) developed by Wischmeier and Smith (1978) was used. Under conditions of data scarcity, the RUSLE, coupled with GIS and remote sensing data, enables grid-based Modeling of soil erosion at a reasonable cost and accuracy (Ganasri and Ramesh, 2016; Haregeweyn et al., 2017; Kouli et al., 2009). Moreover, as the RUSLE can be used for heterogeneous environments and is suitable for estimating soil erosion on a cell-by-cell scale, it can be used to analyze larger scale spatial variability of soil losses. To quantify the gross sediment load entering the irrigation schemes, the sediment yield in the canal systems from surface erosion was combined with the measured river sediment volume (Gurmu et al., 2021). Table 3.2 lists the field data types and sources and the ranges of RUSLE parameter values for the study sites.

Empirically, the RUSLE is expressed as follows:

$$A = R \times K \times LS \times C \times P \quad (3.1)$$

Where A is the mean annual soil loss (t/ha/yr), R is the rainfall erosivity factor (MJ mm/ha h yr), K is the soil erodibility factor (t ha h /ha MJ mm), LS is the slope length and steepness factor (dimensionless), C is the land cover and management factor (dimensionless, ranges from zero to one), and P is the support practices factor (dimensionless, ranges from zero to one).

Table 3.2: Data types and sources and the Revised Universal Soil Loss Equation (RUSLE) model parameters for the study sites

Data type	**Data properties**		**Data sources**
	Ara-Chufa	Ketar	
Discharge			Field collected
Sediment			Field collected
Topography			Field collected
Cross-section geometry			Field collected
Mean Rainfall (mm/yr)	789 (1987 – 2017)	797 (1987 - 2014)	Ethiopian National Meteorology Agency
DEM (12.5 m × 12.5 m)			NASA Earth data https://search.asf.alaska.edu/#/
Soil	Pellic vertisols	Pellic vertisols	International Soil Reference and Information Centre (ISRIC) https://www.isric.org/
Land use	-Bare land -Grassland	-Cropland -Bare land -Closed shrubland -Open shrubland -Open grassland -Open forest	Ethiopian Ministry of Water, Irrigation and Energy

RUSLE parameters	**Schemes**	
	Arata-Chufa	Ketar
R	436	440
K	0.157	0.195
LS	0 – 0.89	0 – 4.2
C	0.13 – 0.4	0 – 0.4
P	0.75 – 0.8	0.7 – 1.0

Source: Gurmu et al. (2021)

3.3 Results

3.3.1 Survey of the Main Canal Systems

Arata-Chufa's main canal had a total length of 1.3 km and supplies water to 10 irrigation blocks (Figure 3.3a). A single canal, with a capacity of 100 L/s, ran from the intake to division box 1 (DB 1) (316 m). After DB 1 the canal split. One part, here labelled Main Canal 1, ran to the pond, from which 60 ha of agricultural lands were irrigated at a capacity of 144 L/s. The second part, here labelled Main Canal 2, irrigated 40% (40 ha) of the irrigable area of the scheme and had a capacity of 100 L/s. The scheme had eight secondary canals with a total length of 3712 m. The topographic survey showed the maximum and minimum elevations of the main canal bed level from the intake to the tail-end to be 1739.6 m and 1731.8 m above mean sea level, respectively (Figure 3.3b).

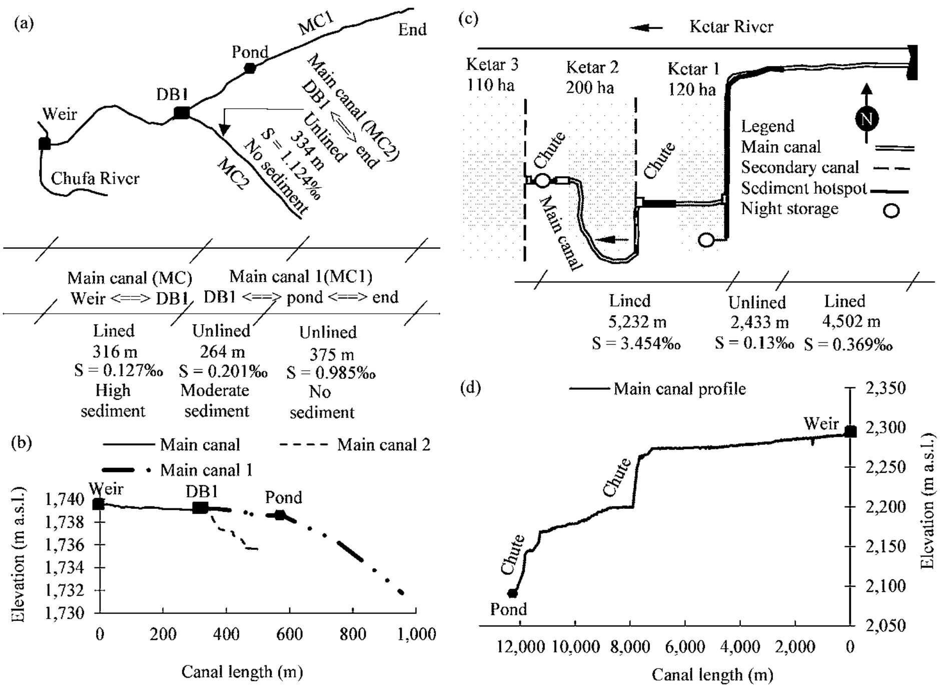

Figure 3.3: Main canal layout (a) and longitudinal profile (b) of the Arata-Chufa scheme and main canal layout (c) and longitudinal profile (d) of the Ketar irrigation schemes.

Note: MC: Main Canal, MC1: Main Canal 1, DB1: division box 1, s: canal bed slope, L: canal length, a.s.l. : above sea level

Ketar had one main canal with a total length of 12.2 km (Figure 3.3c). The scheme consisted of three sub-schemes, namely, Ketar 1, Ketar 2, and Ketar 3. These were located sequentially from upstream to downstream. The main canal had a capacity of 800 L/s for irrigation of 120 ha (Ketar

1) and 200 ha (Ketar 2) during the day. At night water was conveyed to a night storage pond which could hold enough water to irrigate 110 ha (Ketar 3). The main canal bed elevation was measured as 2292.5 m above mean sea level at the intake, 2275.7 m at Ketar 1 (a sediment hotspot section) and 2091.8 at the inlet to the pond at Ketar 3 (Figure 3.3d).

3.3.2 Sedimentation in the Main Canal System

Arata-Chufa was experiencing severe sedimentation. The depth of sediment removed from the canal by farmers ranged from 0.12 to 0.56 m in 2017 (mean = 0.31 m, standard deviation = 0.15 m). In 2018, the quantity of sediment cleaned ranged from 0.12 to 0.55 m (mean = 0.27 m, standard deviation=0.14 m) (Figure 3.4a). Based on interviews with local farmers and WUA leaders, supplemented by examination of sediment marks on the walls of the canal, maximum sediment accumulation depths in 2016 were estimated as ranging between 0.18 and 0.50 m (mean = 0.34 m, standard deviation=0.11 m).

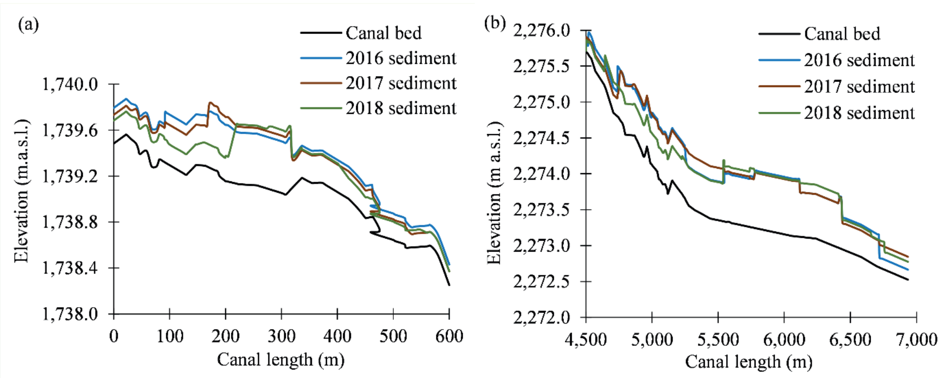

Figure 3.4: Longitudinal profile of the canal bed after cleaning, estimated sediment level in 2016 and measured maximum sediment levels in 2017 and 2018 (before cleaning) at the sedimentation hotspot of the Arata-Chufa (a) and Ketar (b) main canal.

Greater quantities of sediment were removed from the Ketar scheme. In 2017, Ketar farmers cleaned between 0.20 and 0.77 m of sediment (mean = 0.55 m, standard deviation = 0.22 m) (Figure 3.4b). The corresponding amounts cleaned in 2018 were between 0.16 and 0.85 m (mean = 0.51 m, standard deviation = 0.24 m). In 2016, the quantity of sediment removed was estimated at between 0.22 and 0.80 m (mean = 0.56 m, standard deviation = 0.22 m), based on interviews with local farmers and WUA leaders, supported by sediment and flood mark readings.

The sediment accumulation measurements were verified after cleaning the canal, as there was a possibility that farmers might have dug deeper than the design bed level, particularly in the unlined section. The Arata-Chufa desilting campaign was a collective effort for the main canal, while the secondary and tertiary canals were cleaned by the farmers using these sections. The quantity of sediment collectively removed from the Arata-Chufa main canal was 185 and 163 m^3 in 2017 and

2018, respectively (Table 3.3). The desilting campaign to remove this amount of sediment lasted six days in 2017 and five days in 2018, with an average of 4.5 working hours per day. On average, some 794 days of labor per year were required to remove the sediment in these two years. Based on information collected from the interviews, sediment accumulation in the canal was estimated as 194 m^3 in 2016, prior to the fieldwork period.

Table 3.3: Volume of sediment removed from the main canal of the Arata-Chufa and Ketar irrigation schemes during three desilting campaigns.

Canal length	**Annual sediment load (m^3)**		
(m)	2016	2017	2018
Arata-Chufa scheme			
100	26	22	21
200	33	27	20
300	19	21	53
400	70	78	38
500	29	25	18
600	17	12	13
Total	194	185	163
Ketar scheme			
5000	406	397	182
5500	310	298	268
6000	703	709	692
6500	991	970	1062
7000	310	316	319
Total	2720	2690	2522

Note: Data for 2017 and 2018 were measured in late August and early September in those years; 2016 data were estimated based on farmer interviews done in 2017

Very little sediment deposition occurred in the headrace section of the Ketar main canal, from the intake to the sediment hotspot at Ketar 1 (approximately 4.5 km). Excessive sediment deposition occurred in Ketar 1, where farmers diverted water to their field plots. This section was collectively cleaned by farmers from Ketar 2 and 3. Ketar 2 farmers withdrew their irrigation water from the main canal between this sediment hotspot and the pond at Ketar 3. From here, the canal was laid out in a chute structure, and very little sediment deposition occurred. The volume of sediment collectively dredged by the farmers from the problematic section was measured as 2690 and 2522 m^3 in 2017 and 2018, respectively (Table 3.3), and on average 3118 days of labor per year were required to remove the sediment. The volume of sediment removed from the same section in 2016 was estimated as 2720 m^3, based on data and information from local farmers and WUA leaders.

The smallest quantities of sediment were recorded in both schemes in 2018. The average volume of sediment per unit length and unit area were, respectively, 0.3 m^3/m and 1.81 m^3/ha for Arata-Chufa and 1.1 m^3/m and 6.15 m^3/ha for Ketar (Table 3.4).

Table 3.4: Summary results of participatory monitoring for the Arata-Chufa and Ketar irrigation schemes.

Year	Main canal length (km)	Command area of scheme (ha)	Maximum height of sediment deposited (m)	Length of hotspot section (m)	Volume of sediment removed (m^3)	Percentage of main canal with excessive sedimentation (%)	Volume of sediment per unit length (m^3/m)	Volume of sediment per unit area (m^3/ha)
Arata-Chufa scheme								
2016	1.3	100	0.50	600	194	46	0.3	1.9
2017	1.3	100	0.56	600	185	46	0.3	1.9
2018	1.3	100	0.55	600	163	46	0.3	1.6
Ketar scheme								
2016	12.2	430	0.80	2433	2720	20	1.1	6.3
2017	12.2	430	0.77	2433	2690	20	1.1	6.3
2018	12.2	430	0.85	2433	2522	20	1.0	5.9

3.3.2.1 Particle size distribution of the deposited sediments in the main canal system

Sediment was collected from six locations along the Arata-Chufa main canal and the particle size distribution was analyzed. The percentage of sand decreased in the downstream direction, and the percentage of clay increased (Figure 3.5a). There was no well-defined trend in the proportion of silt along the length of the canal. The median particle size at the upstream (22 m), the midstream (256 m), and the downstream (580 m) reaches from the intake is 0.09 mm, 0.04 mm, 0.03 mm, respectively (Figure 3.6a).

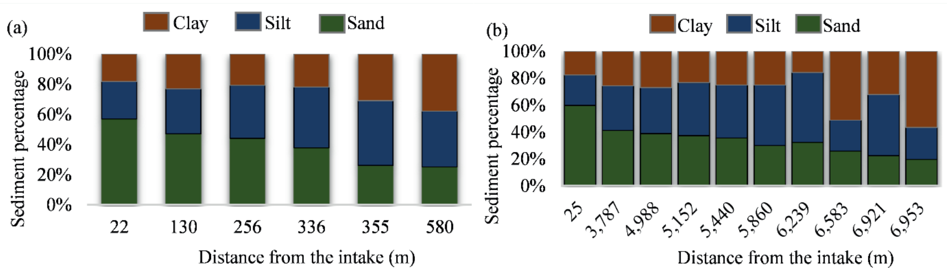

Figure 3.5: Particle size analysis along the Arata-Chufa main canal (six sections) and the Ketar main canal (ten sections).

In the Ketar main canal (Figure 3.5b), the proportion of sand decreased in the downstream direction. The proportion of silt was found to increase in the downstream direction at most of the sampling locations, but then dropped abruptly at approximately 6582 m from the intake. The percentage of clay varied. The median particle diameter at the upstream reach is 0.08 mm, at the midstream reach is 0.03 mm, and at the downstream location is 0.003 mm. Upstream, midstream, and downstream reaches were sampled at 25, 5680 , and 6953 m from the intake (Figure 3. 6b).

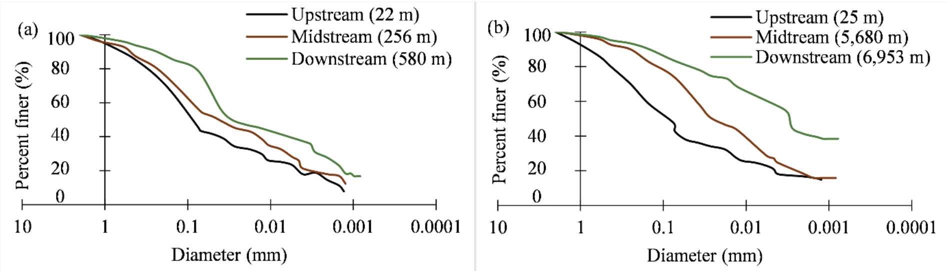

Figure 3.6: Particle size distribution curve at upstream, midstream, and downstream reaches along the Arata-Chufa main canal (at 22, 256, and 580 m) and the Ketar main canal (at 25, 5680, and 6953 m) from the intake.

3.3.3 Sediment Brought in With River Water

The total inflow of irrigation water and the sediment brought in with it were measured during the dry season (September to May) when irrigation was practiced. Irrigation was not used during the wet season (June to August), as crops were mainly grown under rainfed conditions in that period. The annual inflow of sediment with irrigation water at the Arata-Chufa intake was approximately 220 m^3 (Figure 3.7a). Of the gross annual sediment inflow, 11% (24 m^3) was deposited in the pond and some 13% (30 m^3) was transported through Main Canal 2, due to the steepness of the canal (1.124‰), and mainly deposited in the irrigated field plots (Table 3.5).

Table 3.5: Quantity of sediment entering the Arata-Chufa and Ketar irrigation schemes from river water and overland runoff flows.

Annual sediment influx (m^3)	Irrigation schemes	
	Arata-Chufa	Ketar
River sediment	220	1741
Overland flow sediment	8	2042
Total	228	3783
Annual sediment outflux (m^3)	54	592
Annual sediment removed by farmers (m^3)	163	2522

The annual quantity of sediment entering the Ketar irrigation scheme from the river was measured as 1741 m^3 (Figure 3.7b). The quantity of sediment leaving the point of excessive sediment deposition (approximately 7 km from the intake) was estimated as 592 m^3. This sediment ended up in the Ketar secondary canals, sedimentation basin, on the main canal, and night storage pond at Ketar 3.

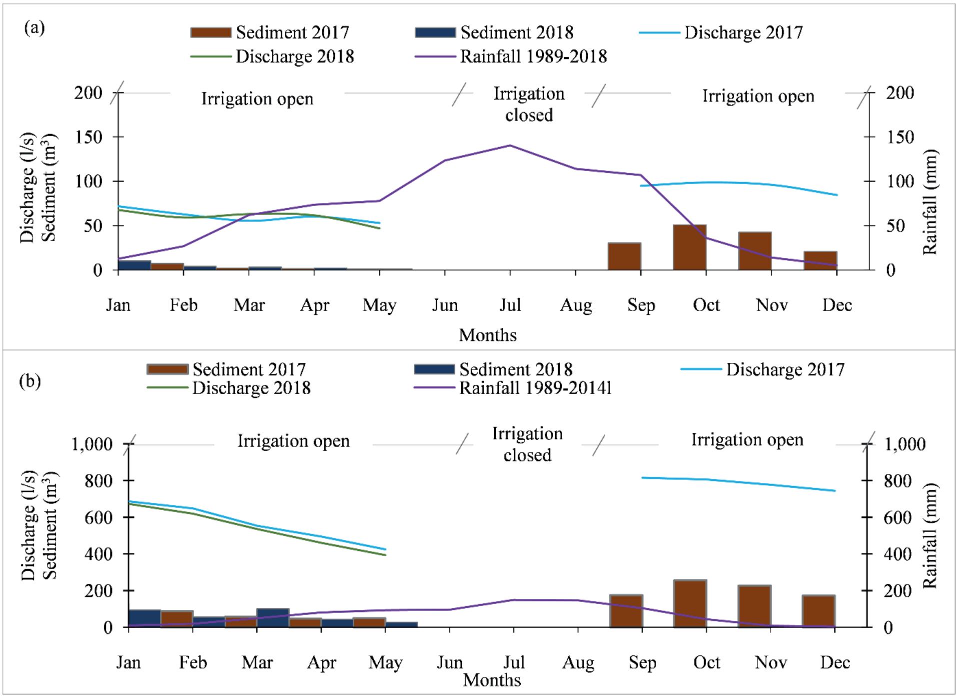

Figure 3.7: Monthly discharge and sediment inflow and the corresponding rainfall amounts at the Arata-Chufa (a) and Ketar (b) irrigation schemes.

Note: Rainfall data were not available for some months

3.3.4 Sediment Inflow with Overland Flow

The catchment – the area beyond the intake structure and upland of the main canal that contributes overland sediment to the scheme – was some 1.14 ha for the Arata-Chufa irrigation scheme (Gurmu et al., 2021). The gross annual soil loss due to overland erosion flows within this catchment was estimated using the Revised Universal Soil Loss Equation (RUSLE) model (Gurmu et al., 2021). The annual soil loss was found to be approximately 29 m^3/yr, with the quantity of sediment expected to end up in the main canal being approximately 8 m^3/yr (Table 3.5) (Gurmu et al., 2021). Nearly 85% of the soil loss comes from the gravel road crossing the main canal, the reminder comes from open grassland found between the gravel road and the main canal (Table 3.5) (Gurmu et al., 2021). Most of the sediment generated from the upland, rainfed cultivated area is diverted to the river by road side ditches (Gurmu et al., 2021).

The layout of the Ketar main canal made it susceptible to excessive sedimentation. The scheme's 4.5 km feeder canal passed through various land use types, including rainfed cropland, before reaching the field plots to be irrigated at Ketar 1. Yet, the structures designed to safeguard the canal against the entrance of surface runoff did not extend over the entire reach of the canal. The gross area potentially contributing sediment to the main canal with overland flows was delineated as 1082 ha (Gurmu et al., 2021). Total soil loss from this area was estimated as 56,697 m^3/yr, and the sediment yield to the main canal was estimated as 2042 m^3/yr (Table 3.5) (Gurmu et al., 2021). About 99% of the overland sediment inflow at the Ketar irrigation scheme came from agricultural fields mainly cultivated with wheat, barely, beans, and maize (Table 3.6**).** Other land uses including close shrubland (0.70%); open shrubland (0.26%); open grassland (0.12%); sparse forest (0.06%); and bare soil (0.01%), contributed the remaining of sedimentation from overland sediment inflow (Gurmu et al., 2021).

Table 3.6: Annual soil loss for land cover types in the Arata-Chufa and Ketar irrigation schemes (Gurmu et al., 2021).

Land use/cover	**Catchment area %**	**Soil loss %**
	Arata-Chufa scheme	
Bare soil/gravel road	57.8	85
Open grassland	42.2	15
	Ketar scheme	
Closed Shrubland	6.0	0.7
Open Shrubland	1.2	0.3
Sparse Forest	0.5	0.1
Annual Cropland	92.0	98.9
Bare Soil	0.0	0.0
Open Grassland	0.3	0.1

3.3.5 Stakeholders' Views on Excessive Sedimentation

Interviews with selected farmers, WUA leaders, and engineers indicated that the problem of excessive sedimentation had worsened over time (Figure 3.8). Though land degradation was the major driver of soil erosion, few of the interviewees seemed to recognize that excessive sedimentation in irrigation works was aggravated by soil losses, which entered the canal with overland flows. Nearly half of the interviewed farmers reported that excessive sedimentation in the canals had gradually caused water stress in the system by reducing canal capacity. Many of the farmers interviewed observed that to maintain an adequate supply of water to the field plots, the main canal needed to be cleaned between once a month and once every three months. At the time, sediment cleaning from the main canal was undertaken annually, or sometimes under heavy sediment conditions, biannually, with the second desilting campaign occurring four to five months after the first cleaning.

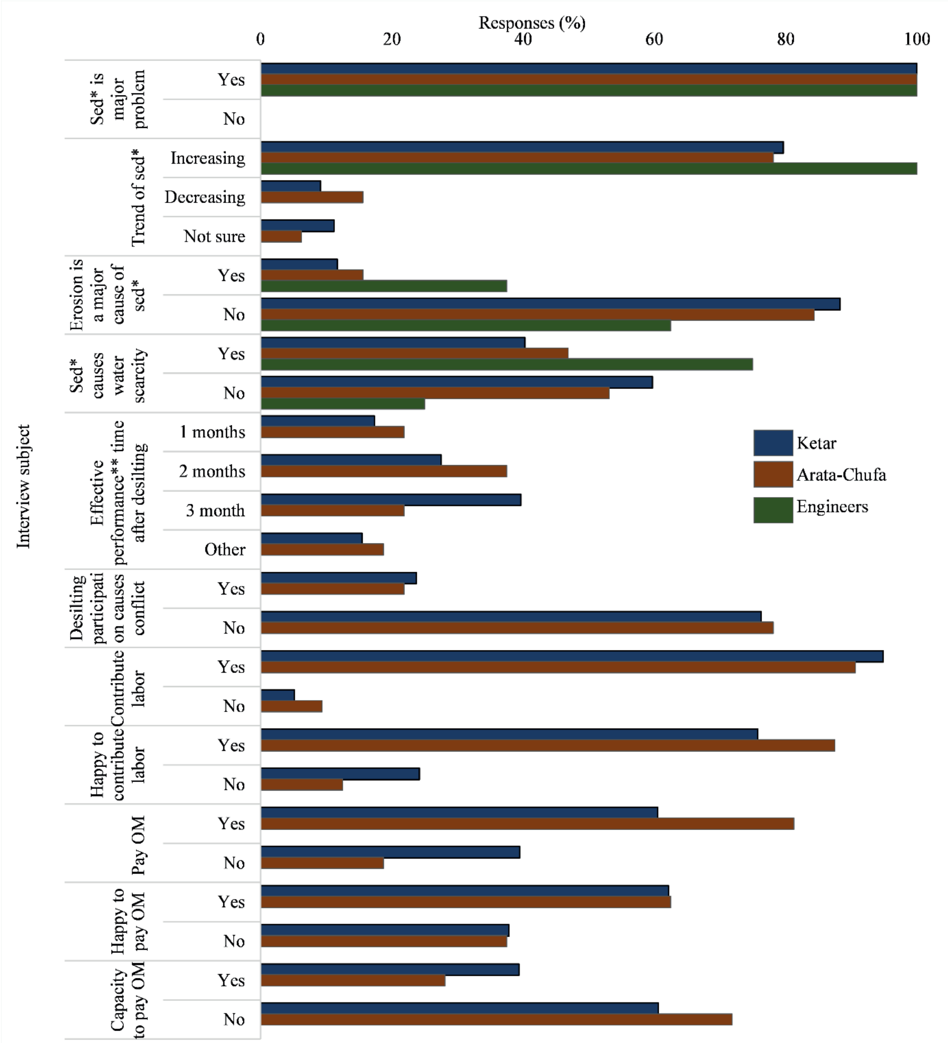

Figure 3.8: Observations on irrigation system performance and cost among farmers and WUA leaders (100 stakeholders) for the Arata-Chufa and Ketar irrigation schemes.

Note: * Sedimentation; ** effective performance time is the length of time the schemes function without problems such as water scarcity or the need for cleaning and maintenance; OM refers to operation and maintenance

Sediment cleaning rarely caused conflict, as local norms and values for operation and maintenance of the system were generally followed by the farmers. This cooperation is ensured sufficient participation in desilting work. However, a few conflicts were reported, arising from sanctions imposed on those who had failed to do their part. All WUA members paid annual O&M fees, in addition to participating in the annual desilting campaigns. Non-member farmers only paid a fee for the water they used to irrigate the land they rented. Well over half (61%) of the interviewed Ketar farmers and more than two-thirds (72%) of the interviewed farmers at Arata-Chufa reported difficulty in paying the annual O&M fees.

3.4 Discussion

The topographic surveys showed that the canal bed elevation played a major role in sediment transport (deposition and scour). Canal sections with milder longitudinal slopes exhibited more sediment deposition than the canal sections with greater slope. For example, the section of the Arata-Chufa irrigation scheme between the headwork and DB 1 (316 m from the intake) was particularly affected by excessive sedimentation. This section of the main canal had a milder longitudinal slope (0.13‰) than the rest of the canal. The slope of Main Canal 1 was slightly greater (0.20‰) from DB 1 to the pond, and then increased further from the pond to the tail-end (0.99‰); the slope of main canal 2 was greater still (1.12‰). For the Ketar irrigation scheme excessive sedimentation was found particularly in the midstream reach of the main canal, approximately 4.5 km from the intake. Here the main canal bed longitudinal slope was milder (0.13‰), compared to the other sections of the canal (0.37‰ from the intake to the sedimentation hotspot and 3.45‰ from the hotspot to the pond at Ketar 3). This confirms that the problem of excessive sediment deposition is especially likely to occur in places where the canal bed has a milder longitudinal slope.

Operations and maintenance aspects, particularly operating gates, also were found to affect sediment transport. The current study is consistent with evidence from previous observations (e.g., (Depeweg and Paudel, 2003; Munir, 2011; Osman et al., 2016; Paudel, 2010; Theol et al., 2019b). Arata-Chufa, for example, was designed with two gates at DB 1, where the main canal divides, forming a T-shape. Farmers opened one of the gates during the day to allow water to flow into Main Canal 2. That gate was closed at night, with the other gate (at a 90 degree angle) opened to allow water into the pond. The operation of the gates, particularly the closing of the first gate, reduced flow velocity, increasing the rate of sediment deposition in the canal. The silt depth was as high as 0.56 m in 2018 at this location.

Although topography is a key factor in the location of irrigation system intake structures, the distance from the intake to the field plots is crucial in determining the quantity of sediment that enters the canal (de Sousa et al., 2019; Theol et al., 2020a). The greater the distance from the intake to the field plots, the greater the observed sediment deposition in the schemes. The Arata-Chufa intake (elevation 1740 m above mean sea level) was approximately 400 m from the field plots (elevation 1732 m above mean sea level). However, the Ketar intake (elevation 2292.3 m above mean sea level) was some 4.5 km from the field plots (2276 m above mean sea level). Ketar also exhibited more severe sediment deposition than Arata-Chufa. The greater distance between the intake and field plots exposed the canal to greater surface runoff. Particle size distribution analysis

3

of sediment samples collected from various locations along the canals showed a decreasing proportion of sand at greater distances from the intake indicating the sand was depositing at upstream locations.

Excessive sedimentation affected about 46% (600 m) of the Arata-Chufa main canal, compared to only 20% (2433 m) of the Ketar main canal. However, based on the volume of sediment removed per unit length of the main canal and command area, the problem was more severe at Ketar. The quantity of dredged sediment per unit length of the canal and command area for Ketar was estimated at 1.1 m^3/m and 6.3 m^3/ha, respectively, in 2016. In 2018, the quantity of sediment deposition measured had decreased by 12 and 6%, respectively, for Arata-Chufa and Ketar. It was not possible to compare this change to rainfall, as rainfall records for the area were incomplete.

Desilting campaigns were organized annually or biannually, lasting from three to five days depending on the quantity of sediment that entered the canal in a specific year. In most cases the desilting was undertaken once a year which is in line with the suggestion of a study by Belaud and Baume (2002) to improve water delivery. Initial desilting was done at the end of the wet season, when the irrigation system remained closed and crop cultivation primarily was rainfed. In consultation with local farmers, the WUA fixed dates for maintenance and sediment removal activities, considering public holidays, the expected start of the irrigation season, weather conditions (cessation of rain storms), and the need to avoid a second round of cleaning due to backwashing of dredged sediment. For both irrigation schemes, even though few farmers start irrigation in the middle of September, the full-scale irrigation season starts in October. The amount of sediment that entered the schemes was measured with river water from September to May. In both irrigation schemes, river water carried a huge sediment load, especially during the rainy season. The maximum monthly sediment inflows from river water were measured as 51 m^3 at Arata-Chufa and 255 m^3 at Ketar. Both of these maximums were recorded in October. In 2018, the quantity of sediment deposited in the Arata-Chufa main canal was 166 m^3 and the quantity of sediment farmers removed was 163 m^3. River water sediment load measurements indicate that sediment deposition in the Arata-Chufa scheme was mainly attributable (95%) to river water sediment. Due to the high intensity of rainfall in the area, some of the sediment entering the canal with river water was transported onto the field plots or to the pond. Overall, the quantity of sediment removed from the canal by the farmers was less than the gross sediment inflow. 1149 m^3 of sediment deposited in the hotspot section of the main canal from the river sediment brought into the Ketar scheme in 2018, and overall 2522 m^3 of sediment was removed by the farmers. Thus, an estimated 46% of the sediment deposition in Ketar can be attributed to sediment load in the river water entering the scheme.

The gross annual soil loss in the Arata-Chufa catchment (1.1 ha) was 29 m^3, and the corresponding sediment yield entering the canal with overland flows was 8 m^3 (Gurmu et al., 2021). If the entire sediment yield of the catchment ended up in the canal, 4% of the sediment deposition in the canal would be attributed to overland flows, which mainly came from the erosion of the gravel road crossing the main canal (Gurmu et al., 2021). Because the soil loss from the upland catchment area is diverted to the river, and, thus, does not end up in the canal, the overland sediment contribution at the Arata-Chufa schemes is quite small. The gross annual soil loss in the Ketar catchment was estimated as 56,697 m^3, and the quantity of sediment that ended up in the canal was estimated as 2,042 m^3 (Gurmu et al., 2021). This means that the sediment contribution from surface runoff ranges between 54 and 77%, depending on the conditions applied. First, if the entire sediment yield from surface erosion was deposited in the canal section from which farmers removed the 2522 m^3 of sediment, the surface erosion contribution would be 77%. If the entire sediment yield from erosion did not end up in the canal or if some of the deposited sediment was eroded or transported to the pond or to secondary canals during the wet season, then the surface erosion contribution would be 54%. Overland sediment inflow to the main canal at the Ketar irrigation scheme is found to be high as the majority of soil loss from the upland catchment was not diverted back to the river. Rainfed agricultural fields contributed 99% of the soil loss at the Ketar irrigation scheme, while less than one-percent of the soil loss came from about five land use types (sparse forest, open grassland, open shrubland, closed shrubland, and bare soil) (Gurmu et al., 2021). As the irrigation plots lie downhill of the main canal, the impact of local irrigation systems on sedimentation in the main canal is insignificant. These two irrigation schemes use gravity water delivery systems (furrows). Furthermore, secondary and tertiary canal canals were constructed at a higher elevation relative to the irrigation plots. The sediment deposition mainly emanates from local rainfed agriculture and was accounted for while developing the RUSLE parameters, particularly with respect to the land cover and management (C-factor) and support practice (P-factor) (Gurmu et al., 2021).

In many irrigation schemes, river sediment is the only or a major source of sediment. This happens, for example, when the river water carries a high sediment load or the main canal is well protected against overland inflows, or if soil erosion is negligible in the area. In some schemes, the overland sediment contribution is considerable. The Ketar irrigation scheme is a practical example for this scenario. One of the reasons is the main canal traversed a distance of some 4.5 km from the intake to the field plot, through various high erosion risk areas (including rainfed cropland) (Gurmu et al., 2021). However, the canal banks at some reaches significantly protected the main canal from huge quantities of overland sediment inflow. The canal berm (bank) in this scheme reduced potential overland flows by 80%. More than two decades of dumping the sediment removed from the canal along the sides of the canal (L = 2433 m) played a major role in diverting surface runoff away from the main canal. The downside of this high berm is that as the height of the sediment pile steadily rises, dredging activities become more laborious for the farmers.

As previously noted, farmers contributed labor and paid O&M fees for managing sediment deposition in their irrigation schemes. Many of the farmers preferred contributing labor rather than cash, due to their low incomes. Among Arata-Chufa farmers, for instance, nearly 88% were happy to contribute labor for sediment dredging, but only 63% were satisfied with the O&M fees that had to be paid. At Ketar, 82% of farmers were happy to participate in canal cleaning, but only 67% were satisfied with the O&M fees. Among Arata-Chufa and Ketar farmers, respectively, 72% and

61% said that they faced financial difficulties that made the O&M fees hard to pay. Even though the irrigation schemes continuously fail to adequately provide a return on investment to a point where paying O&M fees is difficult, the resilience of the farmers to manage sedimentation problems is key for the irrigation schemes to be operational. The farmers spent one-fourth of the time required for producing a seasonal crop on sediment management – annual and seasonal desilting campaigns (Gurmu et al., 2019).

To reduce the sedimentation problem, farmers use their indigenous knowledge to avoid withdrawal of water during times of high sediment concentration (beginning of the cropping season) and deflect surface runoff to prevent its entrance into the main canal. This tacit operation of the irrigation scheme by the farmers to reduce sediment deposition load is similar to the suggestion by previous studies (Depeweg and Paudel, 2003; Munir, 2011; Osman et al., 2016; Paudel, 2010; Theol et al., 2019b). However, the principal difference between the suggestion of these studies and that of farmers' practice is that the suggestion of these studies only is helpful to reduce sediment deposition that comes from the river source.

Although the authors agree that proper operation of the irrigation scheme helps to reduce unwanted deposition of sediment, it may not bring significant and tangible impact in reducing excessive sediment deposition in small-scale irrigation schemes in SSA. The reason for this is as most of the sediment, in some cases, comes from overland flow during non-irrigation season, improving operation during the irrigation season will not help to get rid of sediment deposited in the non-operation period. Therefore, it is argued that identifying sources of sediment and quantifying its relative contribution to overall sediment deposition is vital for reducing sedimentation problems particularly for irrigation schemes located in areas where surface erosion is a severe problem.

Data scarcity is a reoccurring problem for water resources projects. Particularly lacking is monitoring data on resource utilization and management, such as desilting practices. After the Arata-Chufa and Ketar irrigation schemes came into use, very little data was collected. To gain a better understanding of the O&M issues faced in these schemes, for instance, for revitalization works, rapid data collection is required. The current study involved farmers and WUA leaders in data collection to estimate the quantity of sediment deposition in the year prior to the fieldwork period (2017-2018). Ketar farmers and WUA leaders estimated the quantity of sediment deposited in 2016 as 1% and 7% more than the quantity measured in 2017 and 2018, respectively. Interviews with Arata-Chufa farmers indicated that the quantity of sediment in 2016 was 5% more than in 2017 and 16% more than in 2018. Though the farmers might have exaggerated the figures to emphasise their problem, the participatory approach nonetheless appears to be a credible way to collect information and data in situations of data scarcity and to overcome constraints in time and money to collect measured data in real time. Interviewing many subjects (100), conducting the interview at two different locations (two schemes), comparing the results of the two irrigation schemes, and cross-referencing between the two areas were done to reduce the biases in the interview results. Furthermore, correlation analysis between the interview data (2016) and field-collected data (2017 to 2018) revealed an insignificant discrepancy in the sediment load estimated for the irrigation schemes (Gurmu et al., 2021).

3.5 Conclusion

The current study used participatory research to analyze sediment sources and management of sedimentation problems experienced in two irrigation schemes from 2016 to 2018. Topographic surveys, field measurements, and soil erosion modeling were done to estimate the quantities of sediment from river water and surface erosion entering the irrigation schemes in the Great Rift Valley Basin of Ethiopia. The two irrigation schemes exhibited severe sedimentation problems. The annual sediment influx ranges from 228 m^3 (220 m^3 from river water and 8 m^3 from overland flow) for the Arata-Chufa irrigation scheme to 3783 m^3 (1741 m^3 from river water and 2042 m^3 from overland flow) for the Ketar irrigation scheme. Sediment deposition was as high as 0.32 m^3/m in Arata-Chufa and 1.11 m^3/m in Ketar. On average, 794 and 3118 days of labor per year were required to remove the sediment from the Arata-Chufa and Ketar irrigation schemes, respectively. River sediment accounted for 96% of sediment deposition for Arata-Chufa and 46% of sediment deposition for Ketar. Factors causing excessive sedimentation in the studied irrigation schemes included the milder longitudinal slopes of some canal sections, operational practices, and the location of the intake in relation to the field plots, and the absence or inadequacy of canal banks to prevent surface erosion from entering the canal.

The interviews with engineers, farmers, and officials from the water user associations indicated that they recognized excessive sedimentation as a critical challenge in managing irrigation schemes. They also reported increased sedimentation and decreased canal capacities over time. The farmers practiced periodic removal of the deposited sediment, though they were seemingly unaware of its sources and strategies to sustainably address the problem of excessive sedimentation. Farmers also reported difficulty in paying operation and maintenance fees, preferring to contribute labor for desilting campaigns. Participation of farmers in monitoring and field data measurement demonstrated that such local stakeholders can be a reliable data source for water resources management projects in data-scarce regions.

Generally, the current study found that excessive sedimentation was indeed a critical problems in the irrigation schemes examined and the resilience of the farmers to manage sedimentation problem kept the schemes in good working order. Raising the canal banks in line with the annual desilting campaign by the farmers helps to reduce sedimentation problems as overland flow contributes well over half of the sedimentation in the canal for the Ketar irrigation scheme. Improving operation practice during irrigation season has little role to manage off-season sediment influx. Comprehensive soil and water conservation practices play a crucial role in the sustainable prevention of sedimentation for an irrigation scheme. Changing agriculture to a system that limits onsite soil loss via applying best management practices across the country and elsewhere in the world is of paramount importance. Straw checkerboards that brought significant change in controlling wind erosion in China and other parts of the world (Li et al., 2004; Zhang et al., 2018;

Zhaofeng et al., 2018), in conjunction with measures that reduce water erosion, is crucial for sustainable prevention of soil loss in the study area. Therefore, identifying sediment source and quantifying its relative contribution to overall sediment deposition is the basis for tacking sedimentation problems particularly for irrigation schemes situated in areas experiencing high erosion problems.

4

Chapter 4

Sediment Influx and its Drivers in Farmers' Managed Irrigation Schemes in Ethiopia

This chapter is based on:
Gurmu, Z. A., Ritzema, H. P., Fraiture, d. C. M. S., Riksen, M. J. P. M., & Ayana, M. (2021). Sediment Influx and Its Drivers in Farmers' Managed Irrigation Schemes in Ethiopia. Water, 13(13).

4. Sediment Influx and its Drivers in Farmers' Managed Irrigation Schemes in Ethiopia[3]

Abstract: Excessive soil erosion hampers the functioning of many irrigation schemes throughout sub-Saharan Africa, increasing management difficulties and operation and maintenance costs. River water is often considered the main source of sedimentation, while overland sediment inflow is overlooked. From 2016 to 2018, participatory research was conducted to assess sediment influx in two irrigation schemes in Ethiopia. Sediment influx was simulated using the revised universal soil loss equation (RUSLE) and compared to the amount of sediment removed during desilting campaigns. The sediment deposition rate was 308 m^3/km and 1087 m^3/km, respectively, for the Arata-Chufa and Ketar schemes. Spatial soil losses amounts to up to 18 t/ha/yr for the Arata-Chufa scheme and 41 t/ha/yr for the Ketar scheme. Overland sediment inflow contribution was significantly high in the Ketar scheme accounting for 77% of the deposited sediment, while only 4% of the sedimentation at the Arata-Chufa scheme came from overland flow. Feeder canal length and the absence of canal banks increased the sedimentation rate, however, this was overlooked by the stakeholders. We conclude that overland sediment inflow is an often neglected component of canal sedimentation, and this is a major cause of excessive sedimentation and management problems in numerous irrigation schemes in sub-Saharan Africa.

Keywords: **I**rrigation; Sediment; Overland flow; Soil loss

[3] This chapter is based on: Gurmu, Z. A., Ritzema, H. P., Fraiture, d. C. M. S., Riksen, M. J. P. M., & Ayana, M. (2021). Sediment Influx and Its Drivers in Farmers' Managed Irrigation Schemes in Ethiopia. *Water, 13*(13). doi:10.3390/w13131747

4.1 Introduction

Excessive sediment influx hampers the function of many water resource systems and irrigation infrastructures in sub-Saharan Africa, causing storage capacity reductions, opportunity costs and safety hazards (Aynekulu et al., 2009; Haregeweyn et al., 2012; Kondolf et al., 2014; Mekonnen et al., 2015; Moges et al., 2018; Moridi and Yazdi, 2017; Sumi, 2004). The impact of excessive sedimentation is especially high in countries such as Ethiopia, where overland soil erosion is severe and limited resources are available to address the problem (Haregeweyn et al., 2006; Mekonen, 2005; Young, 1998). Soil erosion is a major factor limiting agriculture due to the loss of fertile topsoil. It has a prolonged effect on the agricultural sector as the rate of soil loss exceeds the soil formation rate (Tamene and Vlek, 2008; Vlek et al., 2008).

Soil erosion also affects the overall performance of irrigation schemes. Due to excessive sedimentation, many irrigation schemes have been abandoned or operate far below full capacity (Amede, 2015; Awulachew and Ayana, 2011). In Ethiopia, most irrigation systems are the river diversion type. However, the country's rivers carry huge sediment loads, and therefore are a major source of sedimentation. Although soil erosion from the upland catchment is the ultimate source of sedimentation in many irrigation schemes, the specific source of sedimentation varies with the mechanism through which the sediment enters an irrigation scheme. An irrigation scheme can be threatened by sediment that comes from a river and an overland. River sediment enters an irrigation scheme via an intake structure. For example, Gurmu et al. (2019) found that river sediment contributed more than 95% of the total sediment deposition in the studied irrigation schemes. Nonetheless, overland erosion flow can also contribute large quantities of sediment. The overland sediment inflow from onsite soil erosion of the catchment area after the intake structure (upland of the main canal) happens when the generated soil loss joins the canal after the intake structures. In some schemes, overland flow is the only source of sedimentation. The Bebeks irrigation scheme, for instance, is threatened only by overland sediment inflow (Abera et al., 2019). The scheme is irrigated by entirely sediment-free spring water, nonetheless it performs far below capacity, mainly due to the sediment that entirely comes from an overland flow.

While many stakeholders recognize upstream erosion as a major driver of sedimentation in irrigation canals, most focus on erosion occurring upstream of the intake (Gurmu et al., 2019). However, much of the overland sediment inflow emanates from the catchment upland of the main canal of the scheme itself. Moreover, deposition from overland flow is typically concentrated in the main canals, as secondary and tertiary canals tend to be built at higher elevations relative to field plots, with canals laid along the contour.

A lack of resources for operation and maintenance aggravates problems of excessive sedimentation (Theol et al., 2020a), as the physical infrastructure of many schemes is deteriorated. In farmer-led schemes, farmers apply tacit knowledge to temporarily reduce the quantity of sediment entering their irrigation schemes, for example, by delaying water abstraction when river sediment loads are particularly heavy (Gurmu et al., 2019) and diverting surface runoff to prevent it from entering the canal (Figure 4.1). To clear excessive sedimentation, they organize seasonal or annual desilting campaigns, which are labor-intensive and require participation of many farmers over several days. For example, in one irrigation scheme serving 430 ha with a main canal length of 12 km, some 3,118 labor days were required per campaign to remove the accumulated sediment (Gurmu et al., 2019). Of the total time required for crop cultivation, farmers were found to invest one-fourth of their time in sediment management activities (Gurmu et al., 2019). However, even with this management, farmers have been unable to adequately and sustainably deal with problems of excessive sedimentation.

Figure 4.1: Farmers at the Ketar irrigation scheme diverting surface runoff to prevent sediment from entering the main canal, 25 August 2018.

Sustainable sedimentation management requires identification of sedimentation sources and quantification of their respective contributions. Yet, most studies on sediment transport in irrigation schemes deal mainly with river sediment. Despite taking a greater share of overall sedimentation quantity in the irrigation schemes, little is known about the contribution of overland erosion flow to sedimentation problems. Therefore, in the current research we quantified soil loss and sediment yield and compared it with the sedimentation volume measured in two small-scale irrigation schemes in the Great Rift Valley Basin of Ethiopia – one of the River Basins in the country that exhibit severe soil losses.

4.2 Materials and Methods

4.2.1 Location of the Study

Two representative small-scale irrigation schemes, namely Arata-Chufa and Ketar from Ethiopia, were selected for the study. Both are gravity type river diversion schemes and both are affected by river and overland sediment inflow. Furthermore, both schemes are operated and maintained by farmers, and were in proper use at the time of the research. Farmers devote time and labor to keep the schemes in working order, despite problems of excessive sediment load and deposition. However, both schemes have differences in the sources and quantity of sedimentation, command area size, type and layout and management structure. Figure 4.2 presents the location of the two schemes in the Great Rift Valley Basin of Central Ethiopia, on the lower reach of the Ketar River, a few kilometers before it joins Lake Ziway. Geographically, Arata-Chufa is located at 7°59′ N and 39°02′ E with an average elevation of 1740 m above mean sea level. Ketar was located at 7°49′ N and 39°02′ E at a mean elevation of 2294 m above mean sea level. The Arata-Chufa scheme covers 100 ha and serves 324 beneficiaries. The Ketar scheme covers 430 ha and serves 1,074 beneficiaries.

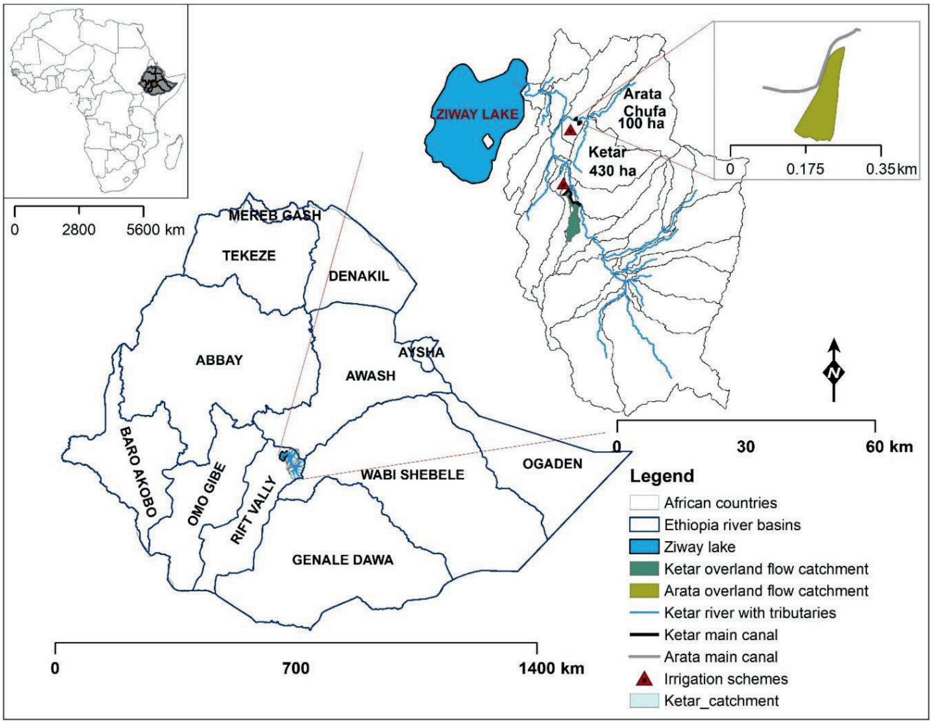

Figure 4.2: Location of the Arata-Chufa and Ketar irrigation schemes and the catchments contributing overland sediment inflow.

4.2.2 Field Data Collection

Field data collection began with an inventory of the schemes, to get acquainted with the canal layout and to understand local conditions, sediment hotspots and canal desilting periods. Farmers reported that desilting campaigns took two to three weeks, with the work conducted only on two to three days in each of those weeks. Canal cleaning and repair activities were undertaken at the end of the rainy season, before the start of the new irrigation season. The summer (wet) season usually ceases in late August. Sediment cleaning activities started in the last week of August and were completed in early September. On average, sediment cleaning took 3 days at Arata-Chufa and 5.5 days at Ketar.

We measured the volume of sediment deposited in the canal and removed by the farmers in two years: 2017 and 2018. The volume of sediment removed in the year before the fieldwork, 2016, was estimated based on the flood marks on the sides of the canal with the participation of farmers. Most canal sections were lined with concrete, which meant that canal cross-sections were relatively uniform. For unlined canal sections, irregularities in canal depth, width and shape were considered in measuring and calculating sediment volumes. Canal transition and culvert sections were measured separately.

4.2.3 Soil Erosion Modeling

There are many empirical models for predicting soil losses and the corresponding sediment yields. However, their scope of application is limited, as they were developed using site-specific empirical data (Ganasri and Ramesh, 2016; Haregeweyn et al., 2017). To deal with this shortcoming, numerical and physically based distributed models have been developed. These, however, require large amounts of input data for calibration and simulation (Kumar et al., 2019) and show limited accuracy in data-scarce conditions (Haregeweyn et al., 2017). Recent advancements in GIS and remote sensing have enabled empirical models to predict soil erosion cell by cell.

Since our study area is characterized by data scarcity, we modeled soil erosion using the revised universal soil loss equation (RUSLE) developed by Wishmeier and Smith (1978) coupled with GIS and remote sensing. Due to its simplicity, RUSLE has been widely applied globally and proven to be of value in the Ethiopian highlands (Haregeweyn et al., 2017; Hurni, 1985a). Figure 4.3 presents our conceptual framework, in which RUSLE was used to identify the main upland sediment sources and to quantify soil loss and sediment yield in the main canals of the schemes under investigation from overland flow sources.

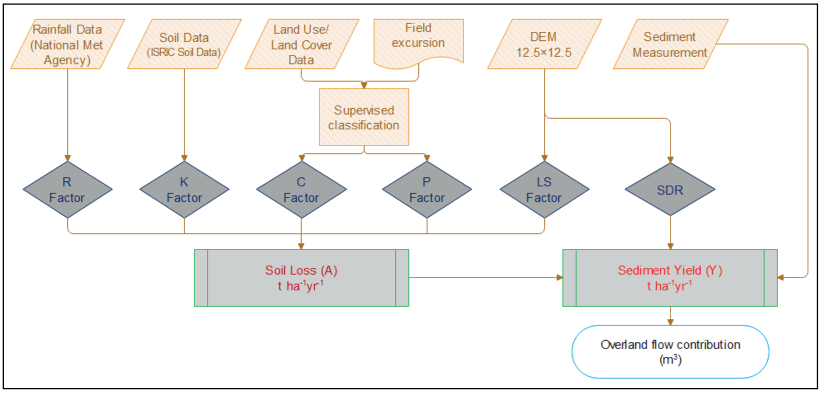

Figure 4.3: Conceptual framework for quantifying soil loss and sediment yield in the canals of the irrigation schemes from overland flow sources.

Usually, the irrigation schemes are closed during the wet season (June to August) and irrigation is resumed after the farmers cleaned their scheme. During the wet season, the sediment enters the canal from the onsite soil erosion of the catchment area upland of the main canal. The volume of the sediment removed by the farmers incorporated both river and overland sediment inflow. We compared the sediment yield computed by RUSLE to the volume of sediment removed by farmers from the canals in their desilting campaigns to estimate the relative contribution of overland sediment inflow to total sediment deposition in the schemes. We conducted transect walks and participatory erosion mapping to identify erosion hotspots and major gully formations. Note that although the RUSLE model is limited in predicting gully erosion, major gully formations were absent in the study area.

Empirically RUSLE is expressed as follows:

$$A = R \times K \times LS \times C \times P \tag{4.1}$$

where

A is the mean annual soil loss (t/ha/yr),

R is the rainfall erosivity factor (MJ mm/ha h yr),

K is the soil erodibility factor (t ha h /ha MJ mm),

LS is the slope length and steepness factor (dimensionless),

C is the land cover and management factor (dimensionless, ranges from zero to one),

P is the support practices factor (dimensionless, ranges from zero to one).

A 12.5 m × 12.5 m digital elevation model (DEM) was used to delineate the catchment contributing overland sediment flow to the canals. First, a larger catchment was delineated taking outlet points in the river a bit downstream to the schemes. Then, many sub-catchments were redelineated considering numerous outlet points in the main canal and the sub-catchments were merged together. Using this method, the catchment contributing overland sediment flow to the Arata-Chufa scheme was delineated as 1.14 ha and it was delineated as 1082 ha for the Ketar scheme.

4.2.3.1 Rainfall Erosivity

Rainfall erosivity (the R factor) measures the ability of the impact of a raindrop to detach a soil particle. It is determined based on rainfall kinetic energy and 30-min rainfall intensity records. However, such rainfall measurements were hardly available for the study area. We thus estimated the R factor, following Hurni (1985b), based on the mean annual precipitation as follows:

$$R = 0.562 \times P - 8.12 \tag{4.2}$$

where P is the mean annual rainfall.

For the Arata-Chufa scheme, we obtained mean annual precipitation for 1987–2017 from Arata station records (Figure 4.4). For the Ketar scheme, nine meteorological stations were nearby. Rainfall interpolation mapping indicated that only the Ketar-Genet station was sufficiently representative of the rainfall characteristics of the catchment of interest. We therefore computed the rainfall erosivity factor using the mean annual precipitation data from the Ketar-Genet station for 1978–2014 (Figure 4.4).

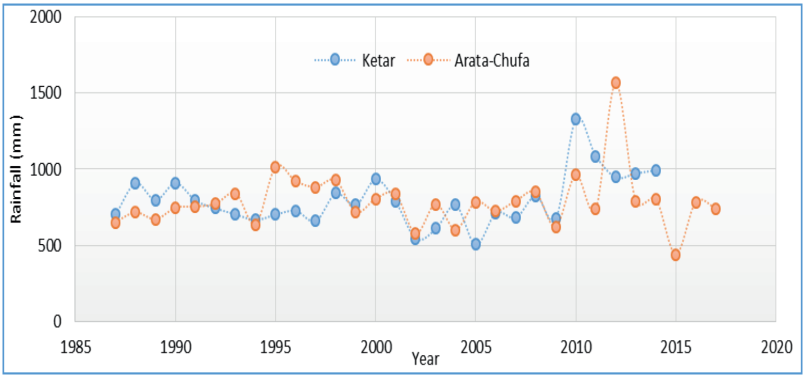

Figure 4.4: Mean annual rainfall for the Ketar-Genet station (7°82′ N and 39°029′ E, altitude 2314 m) and Arata station (7°83′ N and 39°1′ E, altitude 2400 m).

4.2.3.2 Soil Erodibility

Soil erodibility (the K factor) represents the resistivity of soil particles to the impact of a raindrop. K is determined based on soil physical and chemical properties, such as the percentage of silt, clay and sand, organic carbon content and soil structure and permeability (Haregeweyn et al., 2017).

Data scarcity was again an obstacle in the study area. Previous authors (Gelagay and Minale, 2016; Haregeweyn et al., 2017) estimated K values based on observed soil color, as suggested by Hurni (1985b). Williams (1995) estimated K as a function of the percentage of silt, clay and sand and the organic carbon content of the topsoil. We explored different soil databases, including those of the Ethiopian Ministry of Water, Irrigation and Energy, the Ministry of Agriculture and Natural Resources and the Food and Agricultural Organization of the United Nations (FAO). Ultimately, we used data from the International Soil Reference and Information Centre (ISRIC), as it had better resolution (1 km × 1 km) than the other sources. The following function was used to generate a K factor raster map for the catchments:

$$K = f_{csand} \times f_{cl-si} \times f_{org} \times f_{hisand} \quad (4.3)$$

where

f_{csand} is the function of coarse sand content,

f_{cl-si} is the function of the clay-to-silt ratio,

f_{org} is the function of the organic carbon content,

f_{hisand} is the function for high sand content.

Raster files for the above functions were processed in ArcGIS, using the data retrieved from the ISRIC soil database (Figure 4.5), as follows:

$$f_{csand} = \left[0.2 + 0.3 \times (-0.256 \times m_s \times (1 - \frac{m_{silt}}{100})\right] \quad (4.4)$$

$$f_{cl-si} = \left[\frac{m_{silt}}{m_c + m_{silt}}\right]^{0.3} \quad (4.5)$$

$$f_{org} = \left[1 - \frac{0.25 \times orgC}{orgC + \exp\,(3.72 - 2.95 \times orgC)}\right] \quad (4.6)$$

$$f_{hisand} = \left[1 - \frac{0.7 \times \left(1 - \frac{m_s}{100}\right)}{\left(1 - \frac{m_s}{100}\right) + exp\,\langle -5.51 + 22.9 \times \left(1 - \frac{m_s}{100}\right)\rangle}\right] \quad (4.7)$$

where

m_s is the sand content (%),

m_{silt} is the silt content (%),

m_c is the clay content (%),

org_C is the organic carbon content (%).

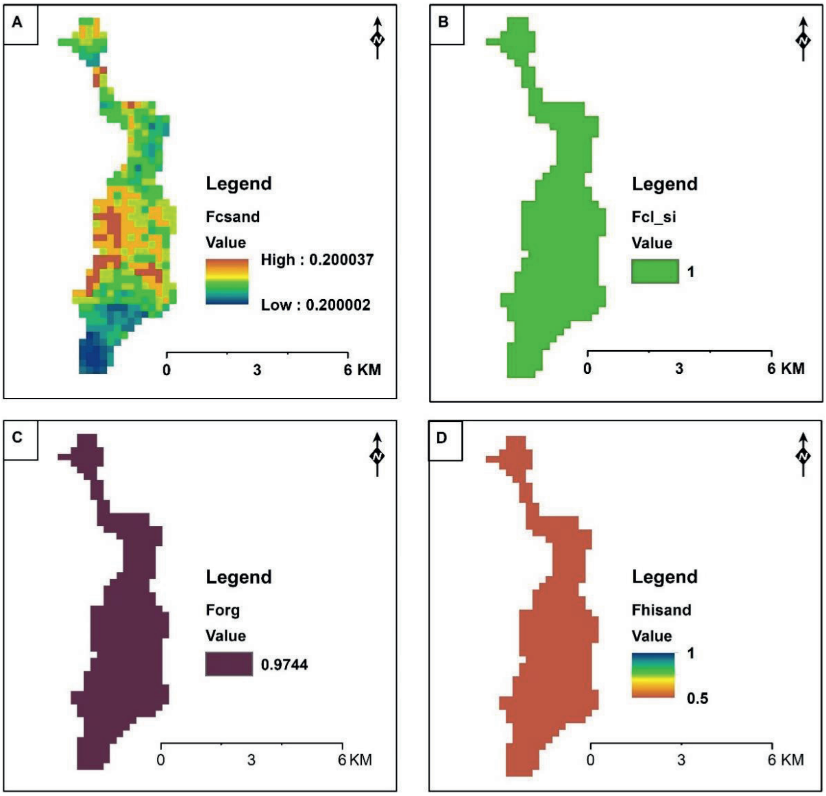

Figure 4.5: Physical and chemical properties of the soil in the study area. a: Coarse sand content; b: clay-to-silt ratio; c: organic carbon content; d: high sand content. Source: Data from the International Soil Reference and Information Centre (ISRIC). Accessed on 3 October 2019; https://data.isric.org/geonetwork/srv/eng/catalog.search#/home.

4.2.3.3 Slope Length and Steepness

Slope length and steepness (the LS factor) represents the rate of soil loss per unit area of land from a field of length 22.13 m and a uniform 9% slope steepness (Wischmeier and Smith, 1978). LS is thus a topographic factor that reflects the sediment transport capacity of surface runoff (Moore and Wilson, 1992). The slope length (L) is the distance from the beginning of surface runoff to a point where either a change in slope occurs or the flow concentrates in depressions (Wischmeier and Smith, 1978). The approach initially introduced by Wischmeier and Smith (1978) to estimate LS did not fully account for the effects of uphill slope and vegetation cover (Qin et al., 2018; Schmidt et al., 2019). Compared to the other erosion parameters, estimation of LS is more controversial for catchments with complex topography (Qin et al., 2018; Schmidt et al., 2019). This is because downhill erosion is determined not only by the erosive power of rainfall and the erodibility of a particular soil, but also by upslope flow accumulation due to uphill topography and land use types and vegetation cover (Qin et al., 2018; Schmidt et al., 2019; Hickey et al., 1994).

To calculate slope length (L) of a complex, three-dimensional terrain, many studies (e.g., (Desmet and Govers, 1996; Gelagay and Minale, 2016; Haregeweyn et al., 2017; Moore and Wilson, 1992; Qin et al., 2018; Schmidt et al., 2019; Wang et al., 2018) adopt a grid-based approach based on the upslope contributing area. The current study used such an approach, as follows:

$$LS = \left(\frac{A_s}{22.13}\right)^m \left(\frac{\sin\beta}{0.0896}\right)^n \tag{4.8}$$

where A_s is the upslope contributing area and β is the slope angle.

Equation (4.9) was used in a GIS environment to generate an LS factor map of the area contributing overland runoff flow to the main canals under study. For this purpose, a 12.5 m × 12.5 m DEM was employed to derive the slope angle to compute the topographic factor.

$$LS = \left(\text{Flow accumulation} \times \frac{\text{Cell size}}{22.13}\right)^{0.4} \times \left(\frac{\sin \text{slope}}{0.0896}\right)^{1.3} \tag{4.9}$$

4.2.3.4 Land Cover and Management

Land cover and management (the C factor) considers the effect of land cover, soil biomass and farming practices on the rate of soil loss (Almagro et al., 2019; Ganasri and Ramesh, 2016). The C factor is the ratio of soil loss with a specific surface cover to the corresponding soil loss from a bare fallow area (Haregeweyn et al., 2017; Kumar et al., 2019; Wischmeier and Smith, 1978). For this study, we mapped the C factor in conformance with land use and land cover maps obtained from the Ethiopian Ministry of Water, Irrigation and Energy and the Ministry of Agriculture and Natural Resources. As the temporal and spatial scale of these maps did not accurately represent real-time land use and land cover conditions in the study area, we minimized uncertainty in C value determination (Panagos et al., 2015; Taye et al., 2018) with supplementation of land use and land cover data gathered during the fieldwork. The development of a C factor map was supported by supervised classification of locally collected land use data, following recommendations from different studies. For agricultural land use types, C values were derived based on the type of farming and slope of the area (Table 4.1).

4.2.3.5 Support Practices

Support practices (the P factor) represents the effect of specific land management practices in reducing runoff and resultant soil losses compared to a situation without those practices with upslope or downslope cultivation (Haregeweyn et al., 2017; Wischmeier and Smith, 1978). The P factor accounts for the effect of structural and non-structural erosion control measures on soil loss. Taye et al. (2018) established *p* values for agricultural and range lands with various soil and water conservation measures in Northern Ethiopia. For the current study in Central Ethiopia, we determined *p* values based on recommendations from the literature (Table 4.1).

Table 4.1: Land cover and management (C factor) and support practices (P factor) values used to compute soil loss with the revised universal soil loss equation (RUSLE).

Land Use/Cover	Description	Slope (%)	*C*	*P*	References
Cropland	Areas intensively cultivated to grain crops with contour planting and no soil and water conservation measures	0–7 7–11.3 11.3–17.6 17.6–26.8 >26.8	0.17 0.20 0.30 0.34 0.4	0.65 0.70 0.75 0.80 0.90	(Almagro et al., 2019; Haregeweyn et al., 2017; Nyssen et al., 2009; Panagos et al., 2015; Shin, 1999; Taye et al., 2018; Wischmeier and Smith, 1978)
Bare soil	Land surface without vegetation cover		0.4	0.65	
Closed shrub	Mixed shrub and grassland, with 50–70% of land area covered		0.1	0.8	
Open shrub	Mixed shrub and grassland, with fair to good cover		0.12	0.75	
Open grassland	Fair to good grass cover (closed grazing)		0.15	0.7	
Sparse forest	Open forest with grassland, with fair to good cover		0.03	0.85	

4.2.4 Sediment Yield

The volume of sediment that ended up in the cross-section of the main canals was computed as a function of the gross soil loss from the catchment contributing surface runoff and the sediment delivery ratio (SDR). Haregeweyn et al. (2008), Nyssen et al. (2009) and Williams and Berndt (1972) developed SDR as a function of catchment physiography, sediment particle size, runoff rate and land use or cover types. The attempt to develop SDR for Ethiopian highlands by Haregeweyn et al. (2008) was reportedly unsuccessful. Jain et al. (2003) computed SDR based on the relationship between suspended sediment and discharge. In a similar study, Haregeweyn et al. (2017), following Nyssen et al. (2009), computed SDR based on land use types with or without soil and water conservation practices and they used a SDR of 30% for agricultural land and 25% for non-agricultural land. Bhattarai and Dutta (2006) derived SDR from overland flow travel time, which is dependent on the terrain and land cover characteristics.

We used the approach suggested by Williams and Berndt (1972), computing the SDR for the study area as follows:

$$\mathrm{SDR} = 0.627 \times \mathrm{SLP}^{0.403} \tag{4.10}$$

where SLP is the slope of the main stream channel (‰).

This method has been found to yield reasonable estimates of sediment yield in data-scarce regions (Kumar et al., 2019; Onyando et al., 2005). As for many empirical equations, this method may not result in an accurate estimate of SDR. Nonetheless, due to limited data availability in the study area, using another option of SDR would still result in the same uncertainty. To minimize the uncertainty, we compared the estimated SDR value computed using this approach with the findings of other studies reported in the country.

We computed the RUSLE factors for the two irrigation schemes under study and used Map Algebra in ArcGIS to quantify the corresponding soil loss and sediment yield. Various statistical analyses were performed to classify the catchment based on soil erosion rates.

4.3 Results

4.3.1 Raster Maps of RUSLE Factors

Raster maps depicting the RUSLE parameters were created for each scheme, Arata-Chufa (Figure 4.6) and Ketar (Figure 4.7). These maps show the spatial distribution of rainfall erosivity (Figures 4.6a and 4.7a), soil erodibility (Figures 4.6b and 4.7b), topography (Figures 4.6c and 4.7c), land cover and management (Figures 4.6d and 4.7d) and support practices (Figures 4.6e and 4.7e). Figures 4.6f and 4.7f present the land cover map of the catchment used to develop the RUSLE parameters for the Arata-Chufa and the Ketar schemes, respectively.

R is uniform for the whole catchment as the mean annual precipitation from a single station used to estimate the rainfall erosivity factor. Note that the catchments were quite small, which limits spatial rainfall variability.

Pellic vertisols were the dominant soil types in the study area. These have a soil erodibility (K factor) of about 0.15 for black cotton soil, estimated from the easily identifiable soil color (Hurni, 1985a). Using the ISRIC soil database, we estimated the K factor as 0.157 for Arata-Chufa and as 0.195 for Ketar. These values were largely in line with the estimated values based on soil color.

The complexity of the terrain affects the computation of the LS factor or slope length and steepness. The Arata-Chufa catchment exhibited moderate topographic variability, with elevations ranging from 1725 to 1730 m above mean sea level. The elevation gradient of the Ketar catchment was larger, with elevations ranging from 2258 m above mean sea level close to the main canal to 2488 m above mean sea level at the upstream escarpment of the catchment.

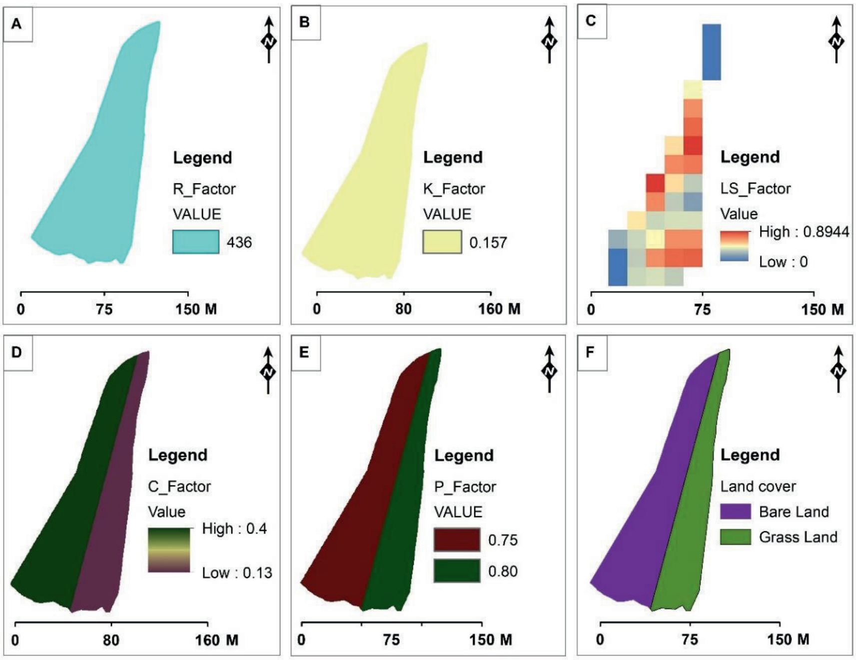

Figure 4.6: Raster maps of catchment contributing overland sediment inflow to the main canal of the Arata-Chufa scheme. a–e depict factors of the revised universal soil loss equation. a: Mean annual soil loss (R factor); b: soil erodibility (K factor); c: slope length and steepness (LS factor); d: land cover and management (C factor); e: support practices (P factor). f: Maps land cover in the study area.

At the Arata-Chufa scheme, sedimentation from surface runoff came mainly from a gravel road that crossed the main canal and an open area of grazing land between the main canal and this gravel road. At the Ketar scheme, various land cover and land use types contributed to the overland sediment flow. Particularly, a rainfed cropland upland of the main canal was the origin of most of the sediment, though there were also mixed grasslands, shrub and open forest in the catchment, with bare areas in between. These characteristics were considered in determining the C factor for the study area. C values ranged from 0.13 to 0.40 for Arata-Chufa and from 0 to 0.4 for Ketar.

No large-scale interventions have been implemented to reduce soil erosion. However, farmers use contour farming and a few have constructed soil bunds at the boundaries of their field plots, particularly at the Ketar irrigation scheme. Moreover, farmers leave biomass on the land after harvesting until the following plowing season. All of these practices help to reduce soil erosion and thus were considered in determining the P factor for the catchments. *p* values ranged from 0.75 to 0.80 for the Arata-Chufa scheme and from 0.65 to 1.00 for the Ketar scheme.

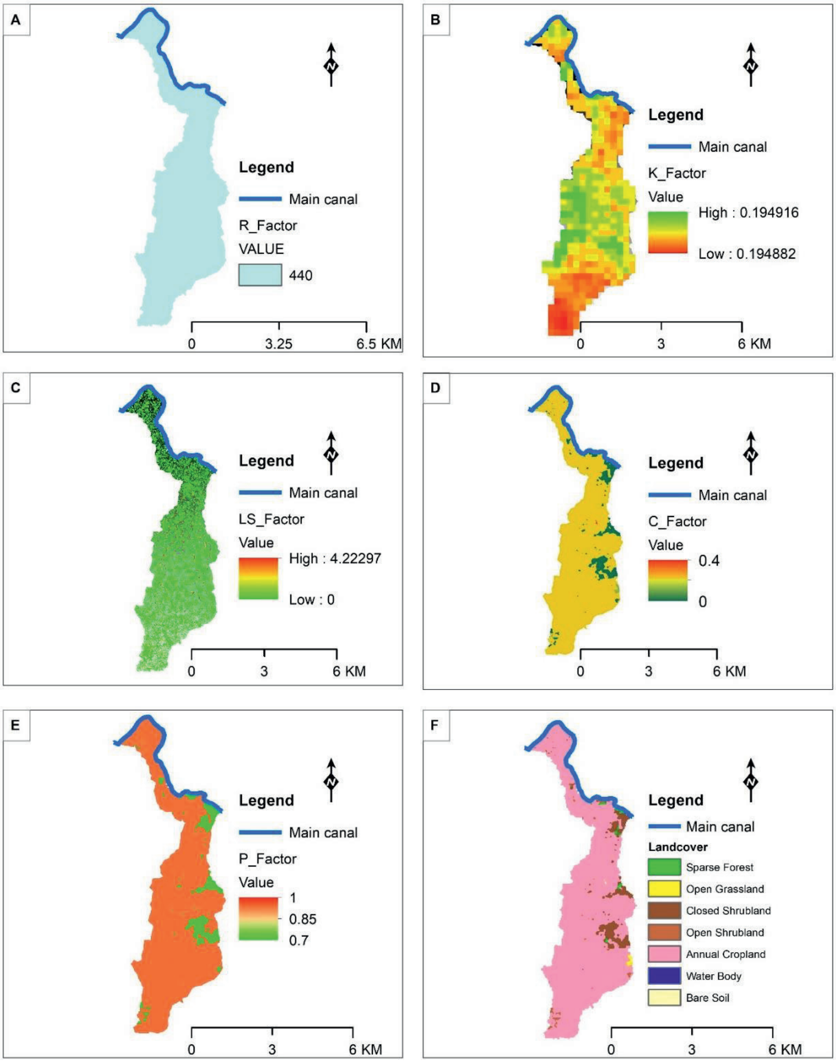

Figure 4.7: Raster maps of catchment contributing overland sediment inflow to the main canal of the Ketar scheme. a–e depict factors of the revised universal soil loss equation. a: Mean annual soil loss (R factor); b: soil erodibility (K factor); c: slope length and steepness (LS factor); d: land cover and management (C factor); e: support practices (P factor). f: Maps land cover in the study area.

4

4.3.2 Estimation of Soil Loss Rate

The pixel-by-pixel estimate of soil loss rates for the catchment of the Arata-Chufa scheme varies from 18 t/ha/yr for bare land (the gravel road) in the upstream part of the catchment to zero for the largely grass-covered zone in the lower catchment, close to the main canal (Figure 4.8a). Mean annual soil loss for the catchment was estimated at 8.9 t/ha/yr, whereas the mean annual sediment yield to the Arata-Chufa main canal from the corresponding catchment was 2.32 t/ha/yr. Sediment yields varied across the catchment, ranging from zero to 4.3 t/ha/yr (Figure 4.8b).

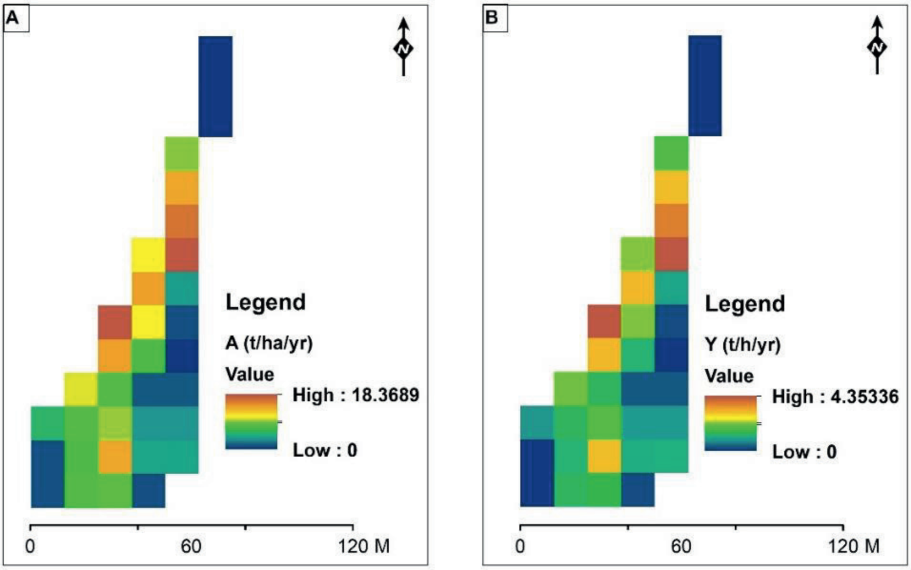

Figure 4.8: Annual soil loss (a) and sediment yield (b) in the catchment contributing overland sediment inflow to the main canal of the Arata-Chufa irrigation scheme.

The grid-based soil loss modeling for the catchment at the Ketar scheme shows annual soil losses ranging from 0, in the lower reach of the catchment, to 41 t/ha/yr (Figure 4.9a). Particularly high soil loss rates were registered along the steep, narrow drainage channels extending upland from the main canal. Mean annual soil loss of the catchment was estimated at 18.5 t/ha/yr, whereas sediment yield to the catchment contributing sediment to the Ketar main canal ranged from 0 to 6.2 t/ha/yr (Figure 4.9b).

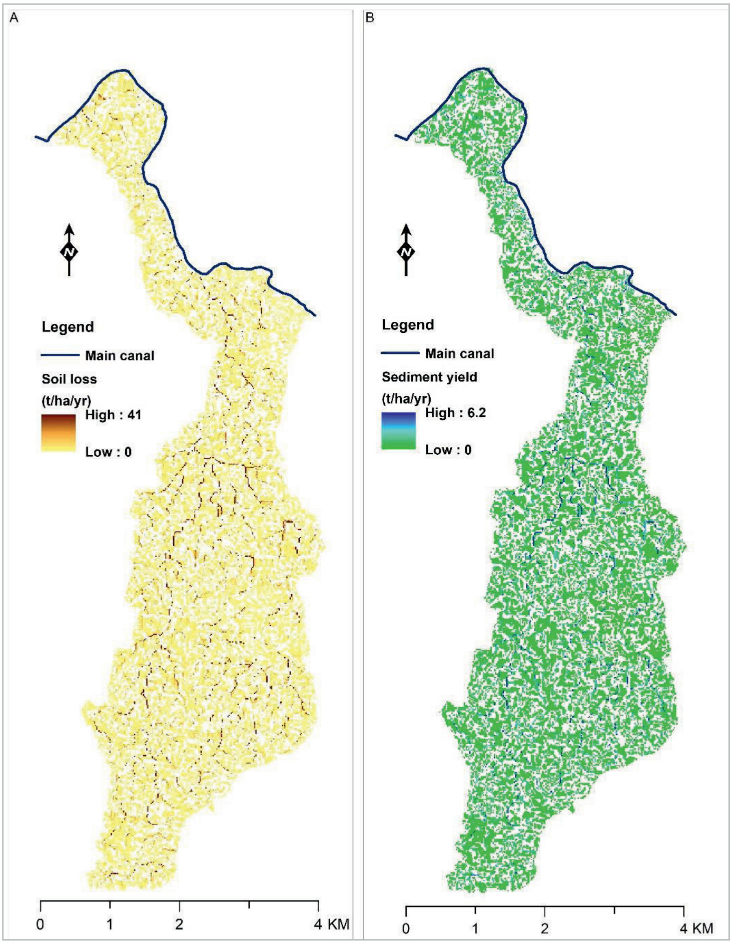

Figure 4.9: Annual soil loss (a) and sediment yield (b) in the catchment contributing overland sediment inflow to the main canal of the Ketar irrigation scheme.

4.3.3 Field Measurement of Sedimentation in the Schemes

Sedimentation, both river sediment and overland sediment inflow, in the main canals of the schemes was measured at the end of the wet season. At the Arata-Chufa scheme, sedimentation averaged 181 m^3/yr. To remove this volume of sediment, some 256 farmers worked 4.5 h a day for 5.5 days, together removing 0.22 m^3 of sediment per day (Figure 4.10, Appendix 4A, Appendix 4B).

Figure 4.10: Volume of sediment removed from the main canal of the (a) Arata-Chufa and (b) Ketar irrigation scheme.

At Ketar, much of the sediment was deposited over only 20% of the main canal (2433 m). This critical section was 4.5 km from the intake and had a milder longitudinal bed slope (0.130‰) compared to the other sections of the main canal. On average, 2644 m^3 of sediment per year was removed from this section of the main canal (see 4.Figure 4.10). Totally 3118 farmers participated in the desilting campaigns, together removing 0.83 m^3 of sediment over three 5-h working days (Figure 4.10, Appendix 4A, Appendix 4B).

Comparison of the volumes of sediment measured in 2017 and 2018 to the sediment volumes estimated for the year prior to the fieldwork (2016) indicate a decrease in sediment volumes from 2016 to 2018, by 10.3% and 4.2%, respectively, for the Arata-Chufa and Ketar schemes. There is a strong correlation between the sediment volume in 2016 and the mean of the sediment volumes in 2017 and 2018, with the correlation being 0.76 for Arata-Chufa and 0.83 for Ketar (Figure 4.11).

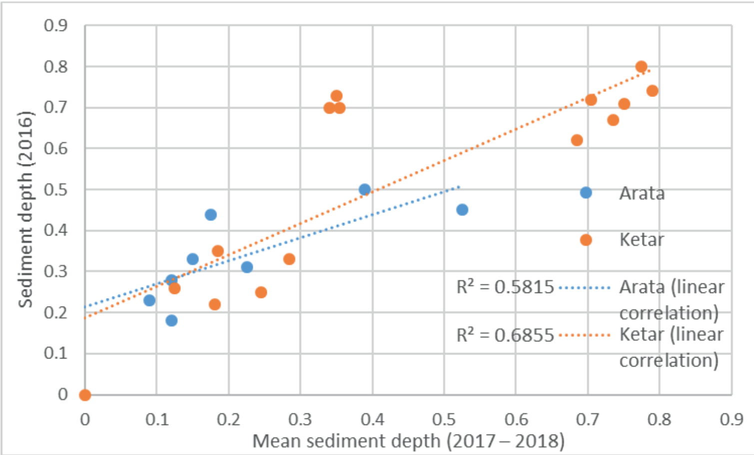

Figure 4.11: Correlation between the mean of the sediment volumes in 2017 and 2018 and the sediment volume estimated for 2016 using flood and sediment marks with farmer participation.

4.3.4 Overland Sediment Inflow Contribution

Overland flow sediment inflow concerns the part of the sediment that comes from the erosion of the catchment area upland of the main canal after the diversion structure and does not enter the scheme via regular intake structures. The onsite overland flow sediment enters the schemes along the main canal lateral. The contribution of overland sediment inflow is estimated by comparing the sediment yield modeled using RUSLE with the gross sediment volume removed from the schemes. The irrigation season runs from September to May (dry season) after dredging the deposited sediment that comes from river and overland flow. During the fieldwork at Arata-Chufa, we observed sediment inflow from surface runoff, despite the small size of the sediment-contributing catchment. Our erosion models indicate that the gross soil loss from this catchment was 10 t/yr. The corresponding sediment yield to the Arata-Chufa main canal was estimated as 2.6 t/yr (Table 4.2).

Table 4.2: Annual soil loss, sediment yield to contributing catchment and quantity of sediment dredged from the main canal of the Arata-Chufa and Ketar schemes.

Soil Loss (*A*)		**Sediment Yield (*Y*)**		**Measured Dredged Sediment**
Rate	**Gross**	**Rate**	**Gross**	**Gross (2016–2018)**
(m^3/ha/yr)	**(m^3/yr)**	**(m^3/ha/yr)**	**(m^3/yr)**	**(m^3/yr)**
Arata-Chufa irrigation scheme				
25.2	28.7	6.6	7.52	181
Ketar irrigation scheme				
52.4	56,697	9.5	2042	2644

The Ketar scheme experienced higher soil loss from the catchment and correspondingly large sediment inflow to the main canal. Gross annual soil loss was estimated as 20,017 t, and the corresponding sediment yield to the main canal of the scheme was estimated as 720 t, with a mean annual sediment yield of 3.44 t/ha (see Table 4.2).

The Arata-Chufa scheme was affected mainly by sediment delivered by the river water feeding the scheme. Most erosion surface flow was conveyed into the river by a channel along the gravel road, which crossed the main canal (Figure 4.12). Measurement of sediment volumes in the main canal and soil erosion modeling indicate that surface runoff contributed about 4.3% (7.5 m^3) of the total volume of sediment deposited in the main canal.

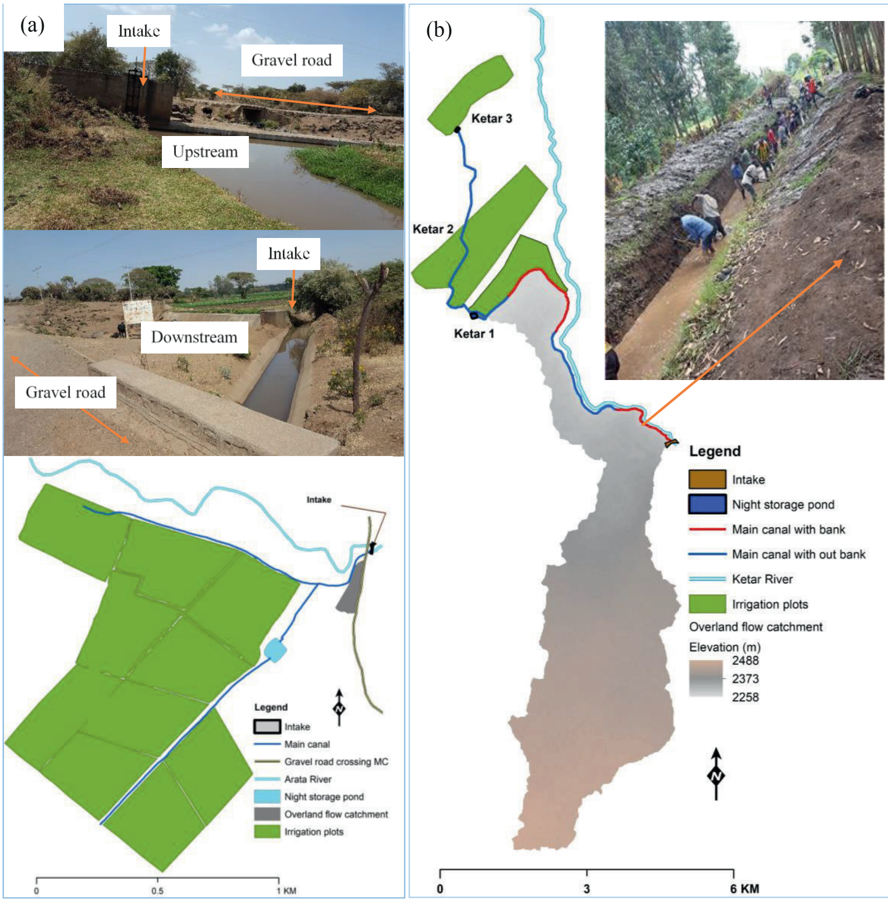

Figure 4.12: Layout of irrigation schemes and overland sediment flow in contributing catchment: (a) Arata-Chufa and (b) Ketar. At Ketar, the main canal segments labeled 'with bank' have a ridge embankment that helps protect the canal against overland sediment inflow.

The Ketar scheme main canal travelled some 4.5 km as a headrace canal from the intake to the field plots through various land use types, though mostly croplands (see Figure 4.12). Moreover, there was a lack of land conservation activities and the main canal was highly deteriorated due to years of use and a lack of maintenance. These factors contributed to overland sedimentation inflow to the main canal. Another factor, however, was the ridges, which had been formed alongside the main canal from sediment removed over years of desilting campaigns. These ridges played an important role in reducing sediment inflow to the canal. Nonetheless, sediment yield analyses show a large contribution of overland sediment inflow to the total volume of sediment deposited in the Ketar main canal. Specifically, overland flows accounted for some 77% (2042 m^3) of the gross volume of sediment deposited in the Ketar main canal.

The Arata-Chufa scheme had a shorter feeder canal. Here, the contribution of overland sediment flow into the main canal was found to be minimal (Table 4.3). Notwithstanding this, the main canal of the scheme became fully silted-up at the end of the cropping season, that is, within a three to four months period. For such a scheme, therefore, overland sediment will likely not be a priority concern. For the Ketar irrigation scheme, however, the volume of overland sediment inflow per unit of main canal was high (167 m^3/km) (Table 4.3). Explanations for this high overland sediment inflow include the long length of the main canal from intake to the first irrigation plot (4.5 km) and a lack of protection of the main canal from overland sediment inflow.

Table 4.3: Overland sediment inflow to the schemes per unit of irrigable land, per length of main canal and per user.

Per unit of Irrigable Land (m^3/ha)	Per Length of Main Canal (m^3/km)	Per User (m^3/farmer)
Arata-Chufa irrigation scheme		
0.08	5.76	0.02
Ketar irrigation scheme		
4.74	167.05	1.90

4.3.5 Soil Loss Severity Analysis

While sedimentation of the Arata-Chufa scheme was found to be due primarily to the entry of sediment-laden river water, with the contribution of overland sediment flow relatively low, it is noteworthy that 92% of overland sediment inflow to the Arata-Chufa main canal came from the gravel road that crossed the main canal (Table 4.4, Figure 4.12).

Table 4.4: Severity classes of soil erosion loss for the area contributing sediment to the main canal of the Arata-Chufa and Ketar irrigation schemes. The severity classes are adapted from Haregeweyen et al. (2017).

Erosion Severity Classes	Range of Soil Loss	Area	Percentage of Total Area	Mean Annual Soil Loss	Total Annual Soil Loss	Percentage of Total Soil Loss
	(t/ha/yr)	(ha)	(%)	(t/ha/yr)	(t/ha/yr)	%
Arata-Chufa irrigation scheme						
Very slight	0–5	0.29	25.44	3.12	0.90	8.42
Slight	5–15	0.75	65.79	10.78	8.09	75.21
Moderate	15–30	0.1	8.77	17.60	1.76	16.37
Severe	30–50	-	-	-	-	-
Very severe	>50	-	-	-	-	-
Total		1.14			10.75	
Ketar irrigation scheme						
Very slight	0–5	1067.7	98.65	0.4	17055.00	70.58
Slight	5–15	10.93	1.01	9.2	3931.00	16.27
Moderate	15–30	3.53	0.33	21.3	2952.00	12.22
Severe	30–50	0.15	0.01	37.8	227.00	0.94
Very severe	>50	-	-	-	-	-
Total		1082			24,165	

At the Ketar scheme, our soil erosion risk analysis indicates that 12% and 1% of sediment deposition in the main canal originated, respectively, from lands classified as ‘moderately’ and 'severely' at risk from soil erosion (Table 4.4). These classes are considered top priority when implementing structural and non-structural soil and water conservation measures. However, the total area of the catchment experiencing moderate to severe erosion rates was quite small compared to the entire catchment size. Indeed, the area exhibiting the highest erosion rates accounted for only about 0.4% of the total catchment area. Thus, to sustainably reduce excessive sedimentation, soil and water conservation activities should be implemented addressing the entire catchment.

4.3.6 Uncertainty in the RUSLE Model

Due to nonlinear spatiotemporal variability of parameters, the RUSLE model is sensitive to input variable uncertainties and the modeling results should be verified using local measurement data (Wang et al., 2002). In particular, the model is highly sensitive to the LS factor (slope length and steepness) (Biesemans et al., 2000; Falk et al., 2010; Herr and Kuhnert, 2007). Moreover, the model cannot predict gully erosion. We used local data to minimize uncertainty in the input parameters and therefore in the model outcomes. Absence of gullies and an overall less complex catchment points to a general reliability of the sediment yield predictions for the Arata-Chufa scheme. At the Ketar scheme, land dynamics were more complex. Nonetheless, considering river sediment and total sediment inflows, the sediment yield volumes estimated by the RUSLE model were in a reasonable range.

4.4 Discussion

The annual soil losses estimated in this study are reasonably close to those reported by other authors from studies in the country. However, our mean annual soil loss estimate (18.5 t/ha/yr) is lower than the national-level estimate of 29.9 t/ha/yr by Haregeweyn et al. (2015) and figures reported for North and North-Western Ethiopia, that is, 27.5 t/ha/yr (Haregeweyn et al., 2017), 47.4 t/ha/yr (Gelagay and Minale, 2016), 42.67 t/ha/yr (Belayneh et al., 2019), 84 t/ha/yr (Selassie and Belay, 2013), 30.6 t/ha/yr (Amsalu and Mengaw, 2014) and 37 t/ha/yr (Yesuph and Dagnew, 2019). In a nationwide study, Sonneveld et al. (2011) reported that mean annual soil losses varied from 0 in the east and south to greater than 100 t/ha/yr in the northern and north-western escarpment. Kebede et al. (2015) conducted a study in the Cheleleka watershed of the Central Rift Valley Basin of Ethiopia, where the current study area was also located. They reported annual soil losses in the range of 2.5–86 t/ha. The current study's mean annual soil loss estimate (18.5 t/ha/yr) is within this range and close to the 18.2 t/ha/yr estimated by Hui et al. (2010).

There is high uncertainty associated with the values estimated using the revised universal soil loss equation (RUSLE) model. To reduce the associated uncertainties, we verified the RUSLE input parameters against the data collected during fieldwork. For instance, the absence or presence of soil and water conservation activities, types of crop, length of the growing period, post-harvest activities, soil type, land use type and absence or presence of gullies were carefully analyzed while determining the RUSLE input parameters. The empirical equation (Equation (4.10)), used to estimate the sediment delivery ratio (SDR), is also subjected to uncertainty. The estimated value of SDR was 26% for the Arata-Chufa and 18% for the Ketar scheme. The estimated SDR values by the current study are close to 30% for agricultural land and 25% for non-agricultural land estimated by Nyssen et al. (2009) as used by Haregeweyn et al. (2008). One reason why our estimated mean annual soil loss is lower than the values reported by other authors for North and North-Western Ethiopia, could be the complexity of the terrain. As noted, topographic complexity plays a substantial role in the estimation of LS, which is a highly sensitive RUSLE parameter (Mahala, 2018). The current study area had moderate topographic complexity, while North and North-Western Ethiopia are well known for their rugged terrain and steep mountains.

Nearly 80% and 26% of the catchments at the Arata-Chufa and Ketar schemes, respectively, exhibited soil loss rates greater than the tolerable limits of 7.2 t/ha/yr (FAO, 1984) and 10 t/ha/yr (Hurni, 1985a). Determination of appropriate tolerable limits is further dependent on local conditions, soil depth, rate of soil formation, terrain and rainfall characteristics. Findings from the current study indicate a need to implement conservation measures before it is too late and degradation becomes irreversible. In most places in the study area, soil was being lost at a rate faster than soil formation, which ranges from 2 to 22 t/ha/yr in Ethiopia (Hurni, 1983). Soil losses greater than 10 t/ha/yr are irreversible within a time span of 50–100 years (Kouli et al., 2009). Land degradation and a lack of conservation measures, particularly on croplands, contributed to high sedimentation rates in the study area. Soil loss in the study area had multiple effects. Among others, it caused deterioration of irrigation infrastructure and soil fertility loss. Many water conveyance and distribution structures had become dysfunctional due to excessive sedimentation and therefore could not deliver the required services. Water shortages, especially late in the irrigation season, were a major problem due to diminished canal capacities, leakages and malfunctioning water distribution structures. Excessive sedimentation also placed a heavy work burden on farmers, to keep the schemes operational. Reduced agricultural productivity due to a loss of nutrients in topsoil was another undesirable effect of soil erosion faced by farmers in the study area. Irrigated fields tended to be farmed under rainfed conditions during the wet season, which also led to an increased risk of soil loss.

The main determinant of the volume of overland sediment inflow appeared to be the layout of the irrigation scheme and upland land cover and land use. From the participatory mapping and transect walk during the fieldwork, we observed that the main canal of the Arata-Chufa scheme was mostly protected against potential overland sediment inflow. Moreover, the main canal extended only some 400 m before it reached the field plots. This short trajectory was of paramount importance in reducing sediment deposition from overland flow. Moreover, sedimentation from surface runoff came from a limited area, particularly, the gravel road that crossed the main canal downstream of the intake and the open area of grazing land between the main canal and the gravel road. The risk of overland sediment inflow at Ketar was substantially higher, as the canal traversed some 4.5 km from the intake to the field plots, through various land uses and land covers. Most of the sediment deposited into the main canal of this scheme originated from the rainfed croplands upland from the main canal.

We computed overland sediment yield into the canals by systematically delineating and classifying the catchments into sub-catchments. This included sub-catchments where banks protected the main canal against surface runoff and sub-catchments without such canal banks, with the latter being more vulnerable to overland sediment flow into the main canal. Across the entire Ketar catchment, which covers 1082 ha, only 215 ha was found to directly contribute overland sediment flow to the Ketar main canal (12.1 km). Furthermore, over more than 30 years of desilting campaigns, Ketar farmers had dumped the sediment removed from the canal alongside the canal, forming a ridge that served to protect some parts of it from overland sediment inflow. However, this sediment ridge had grown to such a height that further sediment dredging activities were nearly impossible. Thus, the farmers were planning to organize a campaign to excavate the sediment accumulated on the banks, to make canal cleaning easier. Considering that with the protection of these and naturally occurring ridges, overland sediment flow still contributed nearly 77% of the total sediment deposited in the main canal, it is recommended that such excavation be done in tandem with construction of canal banks to prevent surface runoff inflow. This would help farmers sustainably address sedimentation problems, and save labor that would otherwise need to be invested in desilting campaigns.

Data scarcity is often a challenge in understanding processes of sedimentation in irrigation schemes and in designing sustainable measures to address excessive sedimentation. Annual sediment deposition in irrigation canals varies depending on many factors, including rainfall intensity and conservation measures to reduce soil loss. The sediment volumes measured in the current study correlated well with the volumes of sediment estimated with the participation of farmers based on flood and sediment marks on the walls of the canals. This is an important finding, as resource limitations often challenge collection of real-time data. Our correlation analysis reveals that a participatory approach can provide a source of reasonable data for conservation measures to deal with problems of excessive sedimentation.

4.5 Conclusions

We measured sedimentation volumes in two irrigation schemes in the Great Rift Valley Basin of Ethiopia in two successive years, 2017 and 2018, and estimated volumes for the year prior to the fieldwork, 2016, based on flood and sediment marks with farmers' support. Sediment inflow to the irrigation scheme main canals from overland flow was modelled using RUSLE. Erosion risk maps were prepared to predict the possible implementation of soil and water conservation measures to reduce soil losses. At Arata-Chufa, 4.3% of sedimentation in the canal was found to come from overland flow, while in Ketar this rate was 77%.

Our soil erosion severity map indicates low to moderate erosion rates in most of the areas under study. Some 84% of the Arata-Chufa catchment and 87% of the Ketar catchment, respectively, demonstrated slight to very slight soil erosion. Areas that exhibited a severe risk of erosion were found along surface drainage channels. Prioritizing soil and water conservation measures in the areas with severe erosion risk would not significantly reduce sediment inflow into the canals, as these covered only a small part of the catchment. Addressing the whole catchment when implementing conservation measures or protecting the main canal from surface runoff by constructing canal banks would be of greater help in significantly and sustainably reducing sedimentation, particularly in the Ketar main canal. Land degradation and a lack of soil conservation measures worsened soil erosion in this study area. In the Ketar scheme, excessive sediment inflow with surface runoff was aggravated by deterioration of the canal, the absence of canal banks and the long distance between the intake and field plots. As a result, water availability diminished as the irrigation season progressed. Moreover, water conveyance and distribution structures became damaged and operation and maintenance costs increased.

Farmers were found to be generally unaware of the source of sedimentation in their schemes. . Identifying these sources and quantifying their contributions provides a crucial starting point for sustainably addressing sedimentation problems. In the Ketar scheme, the overland sediment inflow was found to be huge. This points to the importance of considering overland sediment inflows when rehabilitating irrigation schemes or designing new schemes, to attain optimum conveyance of water and sediment.

Based on these results, three key recommendations are proposed. First, as sources of sedimentation differ for every scheme, identification and quantification of these sources and areas with higher sediment contributions should be the starting point in addressing problems of excessive sedimentation. Second, collaborating with farmers can help engineers and researchers to acquaint with the system and also to provide reasonable data within a short period of time. Third, reduced costs to clean irrigation canals should be included as a direct benefit of soil conservation plans, in addition to such plans' benefits for upland farmers.

Appendix

Appendix 4A: Labor Input and Sediment Output of the Arata-Chufa and Ketar Irrigation Scheme: Adopted from Gurmu et al. (2019).

A	B	C	D	E	F	G
Year	**Farmers Involved (number)**	**Working Hours (h/day)**	**Working Days (days)**	**Sediment Removed (m^3)**	**Total Input (days)**	**Out Put (m^3/day/far**
			Arata-Chufa			
2016	-	-	-	194	-	
2017	260	4.5	6	185	878	0.21
2018	252	4.5	5	163	709	0.23
Average	256	4.5	5.5	181	794	0.22
			Ketar			
2016	-	-	-	2720	-	-
2017	1680	5	3	2690	3150	0.85
2018	1646	5	3	2522	3086	0.81
Average	1663	5	3	264	3118	0.83

Note that 8 h/day of daily working hours is used to estimate labor days and the values from columns A to F are recorded/measured data and columns F and G are calculated values.

Appendix 4B: Farmers Desilting the Sediment from the Main Canal during the Annual Desilting Campaign at the Ketar Irrigation Scheme.

5

Chapter 5

Hydrodynamic Modeling to Develop Design and Operational Options for Sedimentation Reduction in Small-Scale Irrigation Schemes, Ethiopia

This chapter is based on:
Gurmu, Z. A., Ritzema, H. P., Fraiture, d. C. M. S., & Ayana, M.
Hydrodynamic Modeling to Develop Design and Operational Options for
Reduction in Small-Scale Irrigation Schemes, Ethiopia.
Journal of Hydrology: Regional Studies
(under review).

5. Hydrodynamic Modeling to Develop Design and Operational Options for Sedimentation Reduction in Small-Scale Irrigation Schemes, Ethiopia[4]

Abstract

In numerous irrigation schemes in sub-Saharan Africa, sedimentation is a serious problem which causes undersupply of water, raises operational and maintenance costs, and wears out infrastructures. The current study coupled a hydrodynamic sediment model with the output of an erosion model to analyse the existing sedimentation problems in two small-scale irrigation (SSI) schemes in Ethiopia, Arata-Chufa (100 ha) and Ketar (430 ha). The effects of design and operational modifications on sediment reduction were simulated with the Hydrologic Engineering Center's (HEC) River Analysis System (HEC-RAS) model. Canal lining, building a settling basin, and changing longitudinal bed slope were developed as design options, while sediment flushing was formulated as an operational option. For calibration of the HEC-RAS model and simulation, data on discharges, water levels, sediment load, and sediment concentration was collected for two years (September 2017 to September 2018). 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); however, the enormous construction costs would limit its implementation. 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.

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

[4] This chapter is based on: Gurmu, Z. A., Ritzema, H. P., Fraiture, d. C. M. S., & Ayana, M. Hydrodynamic Modeling to Develop Design and Operational Options for Sedimentation Reduction in Small-Scale Irrigation Schemes, Ethiopia. Journal of Hydrology: Regional Studies (under review).

5.1 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, which exert considerable decrease in canal transport capacity. 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, irrigation schemes exhibit severe sedimentation problems. The irrigation schemes in these regions are often vulnerable to both 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 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; Nestore et al., 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 deteriorate when encountered overland sediment inflow at multiple locations 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, 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). 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.

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; Nestore et al., 1998; Osman et al., 2017; Osman, 2015; Paudel, 2010; Theol et al., 2019b). For example, the study by Ali et al. (2021) investigated the role of the design approach to sedimentation problems using the Hydrologic Engineering Center's (HEC) River Analysis System (HEC-RAS) model. Two other similar studies by Osman (2017) and Theol (2019b) investigated the role of scheme operation during peak flood season in reducing sedimentation. These studies focused on reducing river sediment influx in large-scale irrigation schemes equipped with modern structures for controlling water and sediment transport. The current study investigated sediment-reducing options in barely equipped, farmer-managed, 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.

5.2 Materials and Methods

5.2.1 The Study Area

The current study focused on two SSI schemes in Ethiopia with severe sedimentation problems. These were the Arata-Chufa SSI scheme (7^0 59’ N and 39^0 02’ E, 100 ha), affected by sediment that mainly comes from river sources, and the Ketar medium-scale irrigation scheme (7^o 49’ N and 39^o 02’ E, 430 ha), which suffers from a combination of sediment from overland flow and river (Gurmu et al., 2022) (Table 5.1). The Arata-Chufa has two main canals with a total length of 1.3 km and supplies water to ten irrigation blocks (Figure 5.1a). The scheme has eight 3,712 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 schemes 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 (Figure 5.1b) (Gurmu et al., 2019). 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.

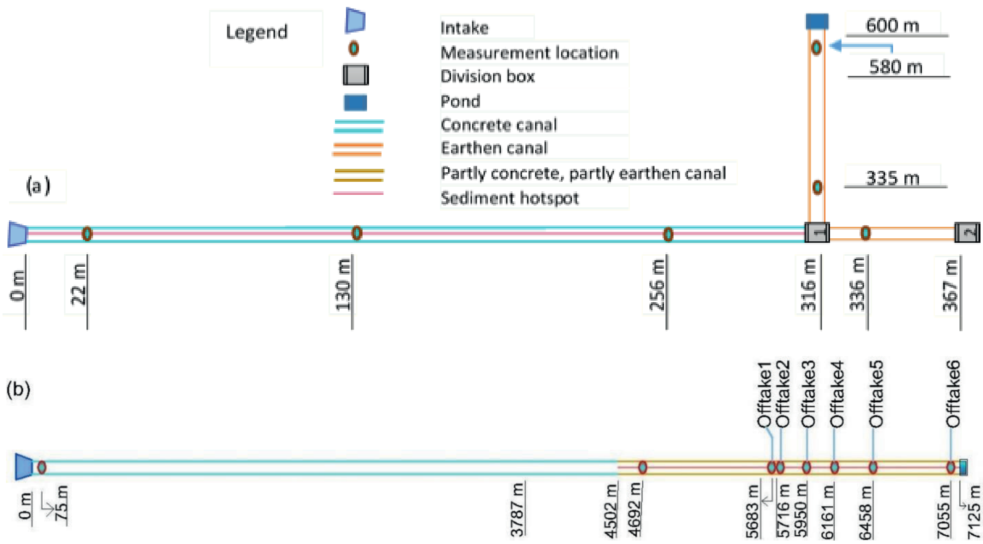

Figure 5.1: Layout of small-scale Arata-Chufa (a) and medium-scale Ketar (b) irrigation schemes. Note that the layout of the two schemes was drawn with different horizontal scales.

Table 5.1: 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	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

5.3 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 (Figure 5.2). 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, topography 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 of the monitoring programme and data analysis, see Gurmu et al. (2022).
- Modeling overland flow sediment yield: the revised universal soil erosion equation (RUSLE) model was used to model overland sediment inflow into the schemes used as boundary conditions for calibration and analysis in the sediment model. For details of RUSLE modeling, see Gurmu et al. (2021).
- A hydrodynamic sediment model: the hydrodynamic Hydrologic Engineering Centre's (HEC) River Analysis System (HEC-RAS) 6.0 model (Brunner and CEIWR-HEC, 2021) was used to analyse the effect of canal design and operation modification on sedimentation.

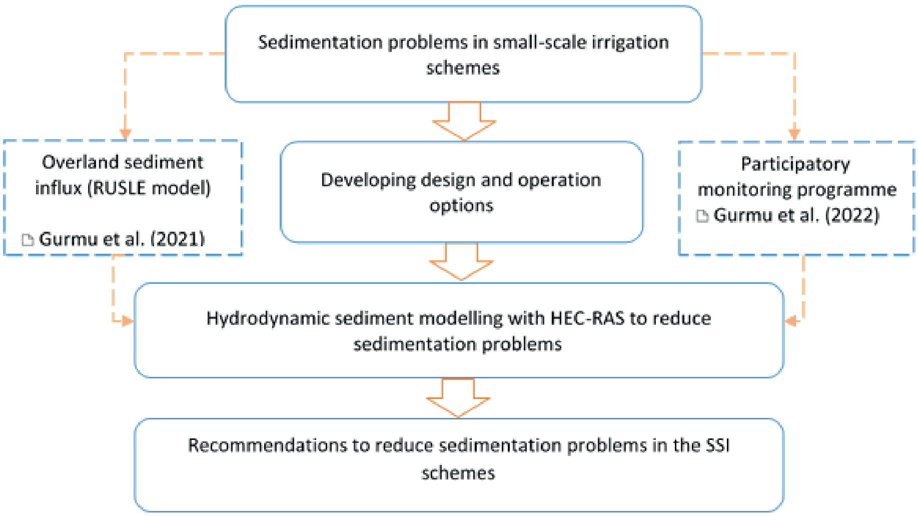

Figure 5.2: Methodological framework used to investigate the effect of design and operation modification on sediment transport in irrigation canals.

5.3.1 Sediment Modeling

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 et al., 2010). There are numerous mathematical models available for open channel simulation, but only a few of the models have sediment transport modules (Munir, 2011; Nestore et al., 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 (Nestore et al., 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 transport model (Paudel et al., 2010). 1D models are widely used to simulate a long-term morphological change in non-wide irrigation canals (Munir, 2011; Paudel et al., 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) (Nestore et al., 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 modeling (Brunner and CEIWR-HEC, 2021). In this study, the open-source 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.

5.3.2 Calibration of the HEC-RAS 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 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. A slight change was made to the Manning roughness to calibrate the sediment model.

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 Appendix 5C.

5.3.3 Scenarios for Reducing Sediment Deposition

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. 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.

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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 (Figure 5.1). 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).

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 option during the rainy season.

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 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.

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.

5.3.4 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 (Brunner and CEIWR-HEC, 2021). 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 to 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 Appendix 5B.

5.4 Results

5.4.1 Calibration and Validation of HEC-RAS Model

5.4.1.1 Calibration of the Hydraulic Model

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 5.2). The calibrated Manning roughness value for each canal reach is presented in the supplementary material, Appendix 5A. 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. Figure 5.3 shows a plot of calibrated water surface elevation simulated by the HEC-RAS model against water levels measured in the Arata-Chufa scheme.

Table 5.2: 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

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 discharge in the canal during both calibration and validation in the Arata-Chufa scheme (Figure 5.4).

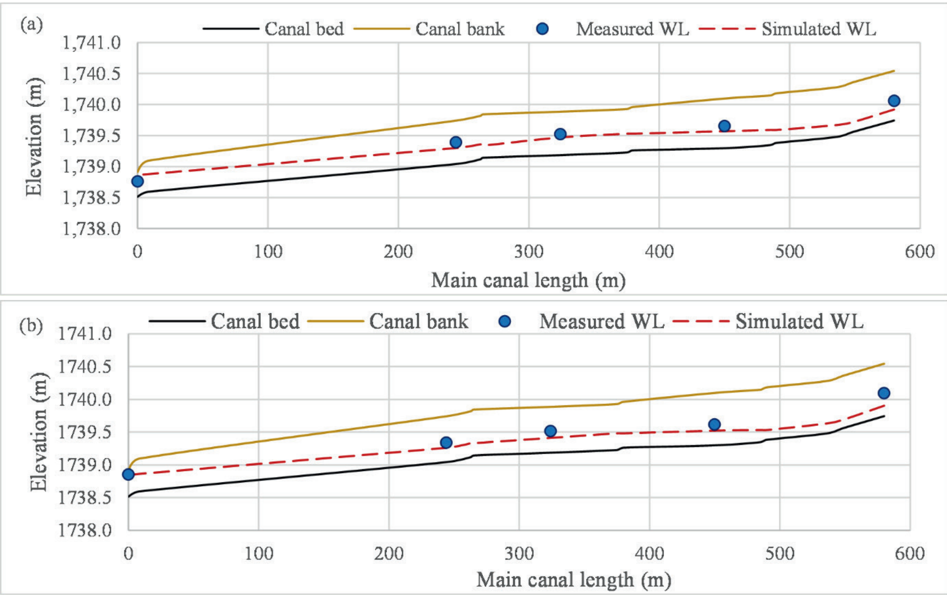

Figure 5.3: Calibration and validation of water surface profile for the Arata-Chufa small-scale irrigation scheme: (a) calibration from September 2017 to May 2018 and (b) validation from January 2017 to May 2017.

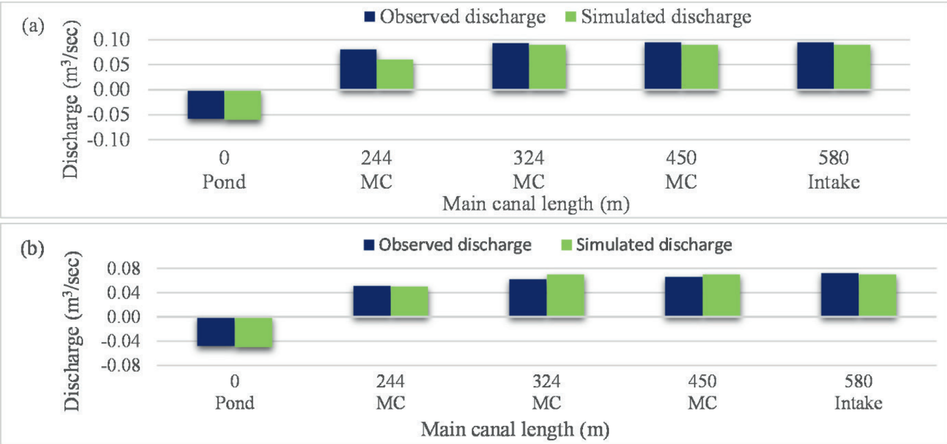

Figure 5.4: Calibration and validation of discharges of the Arata-Chufa small-scale irrigation scheme: (a) calibration from September 2017 to May 2018 and (b) validation from January 2017 to May 2017.

Note: inflow discharges are considered positive and the outflow discharges are considered negative

Figure 5.5 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. 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 (Figure 5.6).

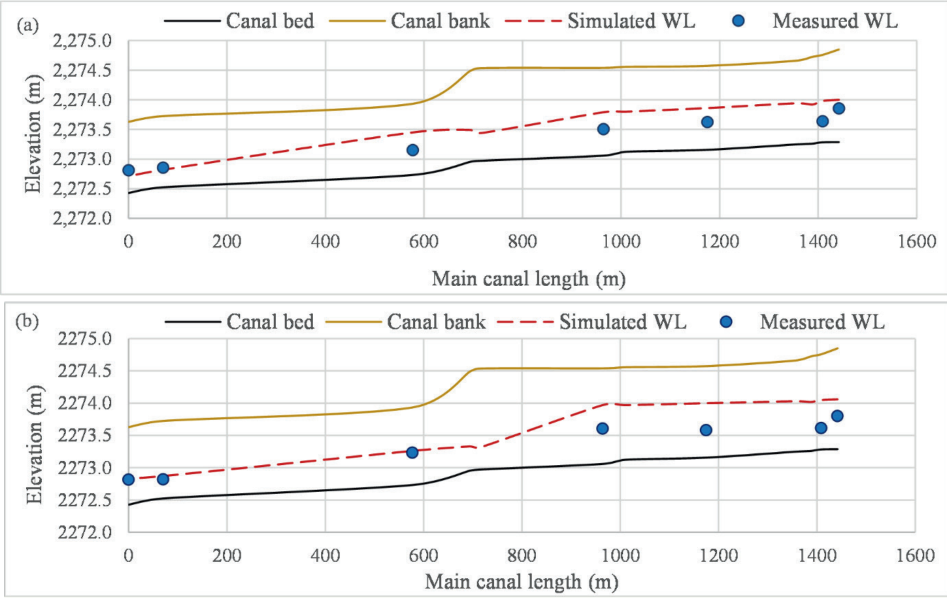

Figure 5.5: Calibration and validation of water surface profile of the Ketar irrigation scheme: (a) calibration from September 2017 to May 2018 and (b) validation from January 2017 to May 2017.

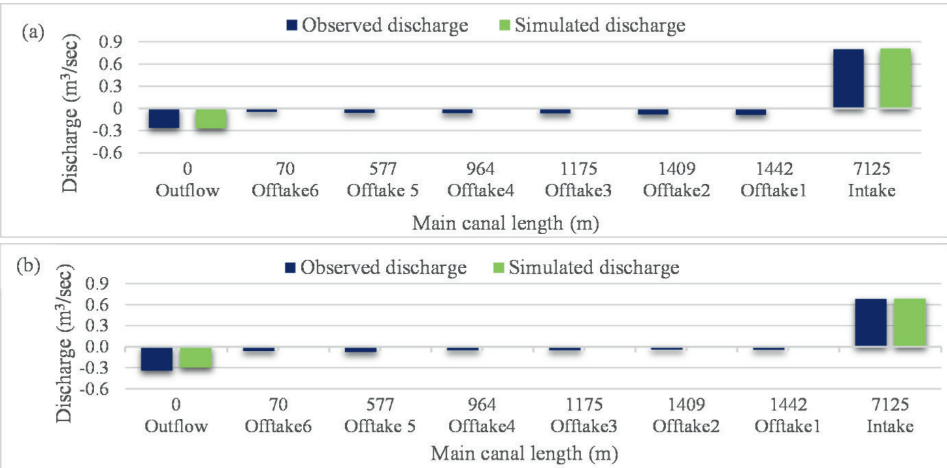

Figure 5.6: Calibration and validation offtake discharges of the Ketar medium-scale irrigation scheme: (a) calibration from September 2017 to May 2018 and (b) validation from January 2017 to May 2017.

After testing the performance of the model in capturing 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 5.3. 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 shows 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 to 0.92 for calibration and validation in both schemes.

Table 5.3: 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**	**$t_{calculated}$**	**$t_{critical}$**	NSEC
			Arata-Chufa irrigation scheme			
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			
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

5.4.1.2 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 (Figure 5.7). The HEC-RAS model in estimating the incoming sediment load and computing the overall sediment deposition performed fairly well. Hence, we conclude that the HEC-RAs model can be used to analyse scenarios that could reduce sedimentation problems in the SSI schemes.

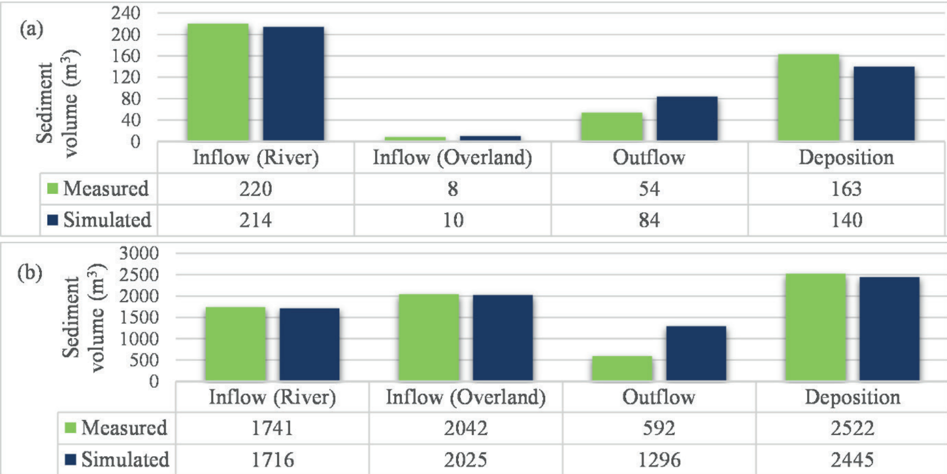

Figure 5.7: Measured and calibrated sediment load in the main canal of Arata-Chufa small-scale irrigation scheme (a) Ketar medium scale irrigation scheme (b), from September 2017 to August 2018.

5.5 Results of Scenario Analyses

5.5.1 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 (Figure 5.1a). 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 canal with rough concrete finishing (n=0.018) could only reduce sediment deposition by less than 15% (Table 5.4).

For the Ketar scheme, the hotspot section is located at the downstream end of the main canal (Figure 5.2a). 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.

Table 5.4: 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 Arata-Chufa:44% unlined (n = 0.03) Ketar: 48% unlined (n = 0.02 – 0.025)	130	780		
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

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

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 (Figure 5.8a). Combing the new settling basin with a flushing option could reduce sediment deposition by some 63%. 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 (Figure 5.8b). 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 to the river.

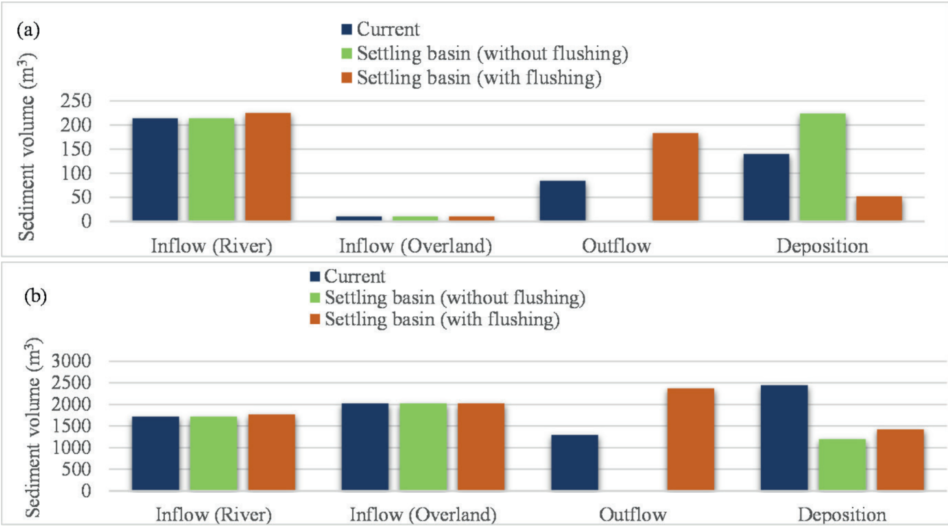

Figure 5.8: Effect of new settling basin on deposited sediment in (a) the Arata-Chufa small-scale irrigation and (b) the Ketar medium-scale irrigation scheme, with and without flushing options.

5.5.3 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. The effect on reducing sediment deposition of raising the bed slope by 5 to 30% was analysed (Table 5.5). 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 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.

Table 5.5: 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				New slope	Ketar scheme: Volume of sediment			
		Inflow	Outflow	Deposited	Deposition decreased		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

5.5.4 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 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 (Figure 5.9). 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.

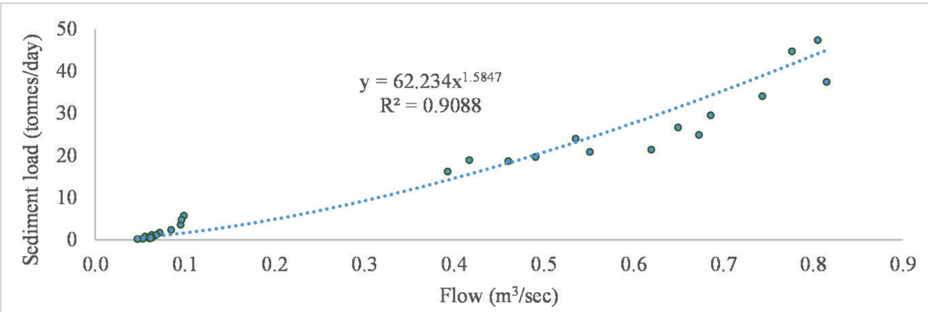

Figure 5.9: Sediment rating curve developed from annual sediment influx at the intake of Arata-Chufa and Ketar irrigation schemes for estimating the rainy season sediment load for selected flushing discharges.

The surface runoff from the catchments discharging overland sediment to the Arata-Chufa and Ketar schemes was computed by the rational method (Table 5.6). The computed runoff was used as a boundary condition in the HEC-RAS model to delimit the overland sediment inflow.

Table 5.6: 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)**		**Run off (Rational method)**	
	(mm)	**(mm)**	**(m^3)**	**(m^3)**	**(m^3/sec)**	**(m^3/sec)**
	Arata-Chufa	**Ketar**	**Arata-Chufa**	**Ketar**	**Arata-Chufa**	**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

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 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 5.7). The sediment could be transported to the pond and field plots via secondary canals. In the Ketar main canal, flushing with 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.

Table 5.7: 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**		**Sediment**	**Deposition decreased**
	River	**Overland**		
	(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

The settling basins without flushing were designed to trap and store the sediment (mainly from the river) prevent the 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.

Table 5.8: 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	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

5.6 Discussion

Numerous gravity irrigation schemes with a long headrace canal experience sedimentation problems, either from river or overland flows. Such problems often originate from design and operational faults. The current study analysed the effect on reducing sedimentation problems of modifying the design (canal characteristics) and changing the operation of the schemes. Short and long-term operational scenarios for tackling sedimentation challenges from overland flow have been included in the discussion, although not modelled with the HEC-RAS.

5.6.1 The Role of Design Changes in Reducing Sedimentation

Some design options can play a considerable role in reducing sedimentation. 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. Analysing three design modifications, the current study showed that changes in morphological design parameters have an effect on reducing sediment deposition. The first of three design scenarios analysed the effect of lining the alluvial part of the main canal with concrete on reducing sedimentation. This was followed by constructing a new settling basin and raising the longitudinal bed slope.

The results of the HEC-RAS model show that the effects of lining the alluvial section of the main canal with concrete differ between the two schemes. While lining reduces sediment deposition in the Arata-Chufa scheme by a little over a quarter (28%), its role is insignificant in the Ketar scheme, reducing sediment deposition by less than 10%. This statistic reveals that lining plays a greater role in reducing river sediment than overland flow sediment. Lining is effective in the Arata-Chufa scheme if more than 80% of the alluvial canal section is lined. Lining is ineffectual in the Ketar scheme, as much of the sediment comes from the overland flow and the unlined canal section has undergone morphological changes (deepening and widening) due to desilting campaigns. This seems to indicate that lining alone cannot increase the sediment transport capacity to a degree that prevents sediment deposition. However, lining reduces seepage, increases discharge and makes delisting campaigns easier – the main reasons why the farmers proposed this option.

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 sediment hotspot section in the Ketar scheme is wider and deeper than the design conditions because the canal has been damaged due to cleaning for several years (Gurmu et al., 2022). Sometimes this section serves as an artificial sediment settling basin, thereby increasing the desilting campaign load. Thus, the sediment cleaning activity needs to be carefully undertaken so that the sediment transport capacity cannot be altered and the sediment cleaning activity aggravated.

The second option 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). The current study simulated construction of a new settling basin with the capacity of one-third of the annual sediment load in the Ketar scheme to store the sediment during the irrigation season. For Arata-Chufa, the settling basin could retain the entire annual sediment load. Three desilting campaigns were considered for the Ketar scheme, while/whereas annual dredging of the sediment was considered for Arata-Chufa. The size of the settling basin can be reduced by increasing the frequency of desilting campaigns; however, the planning depends on how many desilting campaigns the farmers are willing to organize. The cost of construction is also a decisive factor in choosing the size of the settling basin.

The settling basin was designed to trap both river and overland flow sediment with a flushing service as a second alternative. This allows the excess sediment to be flushed back to the river for removal at the lowest possible cost. As most of the sediment is settled in the settling basin, the cleaning costs would be reduced and the desilting campaign made easier. To reduce sedimentation, it seems a sound option in both schemes to combine the construction of a new settling basin with sediment flushing during the rainy season. The combined effect of the new settling basin and a flushing option could reduce sediment deposition by about 63% (Arata-Chufa) and 42% (Ketar) respectively.

The third option analysed was to increase the longitudinal bed slope. This was investigated because lining the alluvial part of the canal alone is not adequate to increase sediment transport capacity and reduce deposition. The sediment transport capacity of the irrigation schemes with long headrace canal 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‰. To analyse the influence of bed slope on sediment reduction, first the impact of raising the bed slope alone was simulated, followed by simulation of the combined effect of raising the bed slope and lining the canal. 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 of only 16.2% for Arata-Chufa and 9.2 % for Ketar (Table 5.8). However, raising the bed slope by 30% and lining the canal ($n = 0.012$) reduced deposition by about 47% in the Arata-Chufa scheme and by 10% in the Ketar scheme.

5.6.2 The Role of Operational Changes on Reducing Sedimentation

Following specific operational practice has a beneficial effect on reducing sediment deposition. For instance, the study by Osman et al. (2017) claimed that operating the scheme depending on actual water need for the crop during periods when excessive sediment is present in the water could reduce sedimentation by half. Another study by Theol et al. (2019b) showed that irregular operation of the gates during periods with high sediment load reduces sedimentation by more than 50%. The current study demonstrated the beneficial effects of changing conventional operations of the intake during the rainy season on sediment deposition. The model results show that flushing the sediment during the rainy season could remove more than 80% of the deposited sediment in the Arata-Chufa irrigation scheme and more than 50% in the Ketar scheme. Opening the intake during the rainy season would allow the canal to maintain its transport capacity, in addition to flushing the deposited sediment during the dry season. This is crucial in avoiding the deposition of overland flow sediment, which is the most dominant sediment source in schemes such as Ketar.

While the sediment flushing scenario completely eliminates sediment dredging costs, its implementation depends on multiple factors. First, 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. The majority of the sediment, particularly in the Ketar scheme, comes from overland flow, not via the intake. Thus, further discussion is needed with the farmers regarding the implementation of this scenario.

Second, the peak discharge during the rainy season could damage irrigation structures. During this season, the river water also transports coarser materials such as gravel, boulders, and tree branches that could potentially break structural components. Some schemes, for instance the Ketar scheme, are designed to withstand peak floods during the rainy season. The first 75m of the main canal of the Ketar scheme was designed to be fully submerged in floods during the rainy season, and the gate at 75m from the intake was designed/intended to stop water and sediment inflow to the main canal. The sediment and the water are conveyed back to the river at this gate location. However, 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. When the sediment is flushed in phases with frequent measurements, one can efficiently evaluate the progress of the flushing.

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.

5.6.3 Uncertainty and Limitation of the Modeling Results

Sediment models with unsteady flow are highly instable, and the accuracy of the model output depends on the accuracy of cross sectional, 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). Performing the sensitivity analysis increases the certainty of the modeling result. 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 (Brunner and CEIWR-HEC, 2021). The HEC-RAS model sensitivity to computational time step was performed for time spans of 1h to 24h, and it was observed that the model gave accurate results for the 1h time step. The reliability of the model's results also depends on the accurate representation of cross-sectional spacing. While 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 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.

5.7 Conclusion

The current study investigated measures for reducing sedimentation in farmer-managed SSI schemes suffering from river and overland flow sediment. As a case study, we selected two small scale irrigation schemes located in Ethiopia which have different sources of sedimentation. These were the Arata-Chufa (100 ha) scheme, which mainly exhibits river sediment, and the Ketar scheme (430 ha), which suffers from a combination of overland flow and river sediment. The study analysed how design modifications (canal characteristics) and operational changes can reduce sedimentation. The study employed a hydrodynamic HEC-RAS model coupled with the output of the RUSLE, an empirical erosion model recognized as a standard method, to calculate the average risk of erosion and to simulate the effects of morphological design parameters and operational modifications on sedimentation. 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. Flushing would reduce more than 80% of the sediment deposition in the Arata-Chufa scheme and more than 50% in the Ketar scheme. Although implementing this option in practice involves no operational cost, further analysis is needed from the operational point of view, and to assess the willingness of the users to adopt it. The second option is lining the alluvial part of the canal, particularly in the Arata-Chufa scheme 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 construction. Nonetheless, construction of a new settling basin without flushing is a good option to minimize sediment deposition in the canal, to increase canal capacity, and to reduce the length of desilting campaigns. Increasing the longitudinal bed slope of the canal could only reduce sedimentation to a limited extent in the existing schemes. This is because modifying one design parameter alone does not produce a sediment transport capacity high enough to convey the incoming sediment load. This problem is mainly due to the damage done to other design parameters, for example, canal depth, width, and bed slope, by manual dredging of the sediment for several years. 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.

Appendix

Appendix 5A1: Calibrated Manning's Roughness of Main Canal Profile of Arata-Chufa Small-Scale Irrigation Scheme.

Station (m)	Bed (m)	Bank (m)	Bottom (m)	Top (m)	Profile	Manning roughness
0	1738.514	1738.914	0.4	0.4	Rectangular lined	0.013
8	1738.592	1739.092	0.5	0.5	Rectangular lined	0.016
244	1739.041	1739.741	0.5	0.5	Rectangular unlined	0.030
263	1739.119	1739.819	0.5	0.5	Rectangular unlined	0.030
265	1739.143	1739.843	0.8	0.8	Rectangular lined	0.017
324	1739.185	1739.885	2.2	0.5	Trapezoidal lined	0.020
375	1739.227	1739.927	2.2	0.5	Trapezoidal lined	0.018
380	1739.261	1739.961	2.2	0.5	Trapezoidal lined	0.015
450	1739.297	1740.097	1	1	Rectangular lined	0.018
485	1739.346	1740.146	1	1	Rectangular lined	0.018
490	1739.382	1740.182	2.2	1	Trapezoidal lined	0.019
536	1739.479	1740.279	0.7	0.7	Rectangular lined	0.018
549	1739.562	1740.362	2.2	0.5	Trapezoidal lined	0.020
580	1739.743	1740.543	2.2	0.5	Trapezoidal lined	0.020
600	1739.921	1740.721	2.2	0.5	Trapezoidal lined	0.020

Appendix 5A2: Calibrated Manning's Roughness of Main Canal Profile of Keta Medium-Scale Irrigation Scheme.

Station (m)	Bed (m)	Bank (m)	Bottom (m)	Top width (m)	Profile	Manning roughness (n)
0	2272.429	2273.629	2.2	2.2	Rectangular unlined	0.022
70	2272.525	2273.725	2	2	Rectangular unlined	0.021
577	2272.733	2273.933	2.2	2.2	Rectangular unlined	0.025
694	2272.955	2274.555	2.2	2.2	Rectangular unlined	0.023
717	2272.973	2274.573	0.7	2	Trapezoidal lined	0.013
964	2273.059	2274.659	2.2	2.2	Rectangular unlined	0.023
1011	2273.124	2274.724	2	2	Rectangular unlined	0.023
1175	2273.157	2274.757	2	2	Rectangular unlined	0.023
1355	2273.248	2274.848	2	2	Rectangular unlined	0.023
1388	2273.261	2274.861	0.7	2.2	Trapezoidal lined	0.014
1409	2273.284	2274.874	2	2	Rectangular unlined	0.022
1442	2273.288	2274.488	2	2	Rectangular unlined	0.023
1578	2273.336	2274.536	2	2	Rectangular unlined	0.023
1588	2273.339	2274.539	0.7	2.2	Trapezoidal lined	0.014
2481	2275.212	2276.412	2	2	Rectangular unlined	0.020
2608	2275.664	2276.864	0.7	2	Trapezoidal lined	0.012
2623	2275.699	2276.899	2	2	Rectangular unlined	0.020
2659	2275.763	2276.963	0.7	2.2	Trapezoidal lined	0.012
3014	2276.962	2278.162	2	2	Rectangular unlined	0.020
3481	2278.231	2279.031	0.7	0.7	Rectangular lined	0.012
4116	2279.956	2280.756	2.2	2.2	Rectangular unlined	0.020
4143	2280.021	2281.221	4	4	Rectangular lined	0.012
4720	2283.459	2284.259	0.7	2.2	Trapezoidal lined	0.012
4728	2283.494	2284.494	2	2	Rectangular steel	0.013
5627	2286.092	2286.892	0.7	2	Trapezoidal lined	0.020
6672	2289.323	2290.123	0.7	2	Trapezoidal lined	0.012
6685	2289.391	2290.591	0.7	2	Trapezoidal lined	0.012
7050	2291.404	2292.404	1	1	Rectangular steel	0.013
7125	2291.823	2292.523	0.7	0.7	Rectangular lined	0.012

Appendix 5B: Sensitivity Analysis of the HEC-RAS Model for the Arata-Chufa and Ketar Irrigation Schemes (Invert Changes for Various Computational Time Increment and Manning's Roughness).

Cross section	Invert change (sediment deposition) (m)													
	Time increment (h)						Manning's Roughness (n)							
	1	3	6	9	12	24	0.013	0.014	0.015	0.016	0.017	0.018	0.019	0.02
Arta-Chufa Irrigation scheme														
0	0.13	0.25	0.10	0.11	0.10	0.26	0.11	0.13	0.13	0.13	0.12	0.12	0.12	0.11
8	0.09	0.19	0.06	0.07	0.07	0.16	0.06	0.09	0.09	0.09	0.09	0.09	0.08	0.08
126	0.14	0.20	0.03	0.06	0.06	0.06	0.03	0.14	0.14	0.14	0.14	0.14	0.14	0.12
244	0.38	0.39	0.25	0.28	0.22	0.23	0.22	0.38	0.37	0.37	0.38	0.38	0.38	0.33
263	0.34	0.35	0.16	0.19	0.23	0.07	0.13	0.34	0.33	0.33	0.33	0.34	0.33	0.29
265	0.36	0.37	0.24	0.26	0.25	0.16	0.20	0.36	0.35	0.35	0.35	0.36	0.35	0.31
324	0.37	0.38	0.26	0.28	0.26	0.13	0.23	0.37	0.36	0.36	0.36	0.36	0.36	0.32
375	0.43	0.44	0.36	0.37	0.35	0.22	0.33	0.44	0.43	0.46	0.43	0.43	0.44	0.44
380	0.42	0.41	0.33	0.34	0.32	0.20	0.30	0.43	0.41	0.42	0.41	0.41	0.42	0.39
450	0.45	0.44	0.48	0.42	0.40	0.27	0.46	0.45	0.44	0.45	0.44	0.44	0.45	0.44
485	0.42	0.41	0.54	0.46	0.41	0.28	0.54	0.42	0.42	0.46	0.41	0.41	0.42	0.44
490	0.43	0.42	0.53	0.44	0.38	0.26	0.51	0.43	0.42	0.43	0.43	0.43	0.43	0.42
536	0.35	0.33	0.54	0.44	0.38	0.22	0.53	0.35	0.34	0.33	0.35	0.35	0.34	0.35
549	0.34	0.33	0.53	0.43	0.34	0.18	0.49	0.34	0.34	0.33	0.35	0.34	0.34	0.50
580	0.42	0.42	0.64	0.37	0.33	0.15	1.21	0.42	0.42	0.36	0.44	0.44	0.41	0.67
Ketar irrigation scheme														
964	0.26	0.27	0.27	0.27	0.27	0.27	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26
1011	0.25	0.25	0.26	0.26	0.25	0.26	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
1175	0.17	0.18	0.18	0.19	0.19	0.19	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
1355	0.37	0.38	0.38	0.39	0.39	0.39	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
1388	0.21	0.22	0.22	0.23	0.22	0.23	0.20	0.21	0.20	0.20	0.20	0.21	0.20	0.20
1409	0.39	0.40	0.40	0.40	0.40	0.40	0.38	0.39	0.38	0.38	0.38	0.38	0.38	0.38
1442	0.42	0.44	0.44	0.45	0.45	0.45	0.42	0.43	0.42	0.42	0.42	0.43	0.42	0.42
1578	0.63	0.64	0.64	0.65	0.64	0.65	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63
1588	0.49	0.51	0.50	0.51	0.51	0.51	0.49	0.49	0.49	0.48	0.48	0.49	0.48	0.49
2008	0.39	0.41	0.40	0.41	0.40	0.40	0.40	0.40	0.39	0.39	0.39	0.40	0.39	0.40
2481	0.29	0.28	0.26	0.26	0.25	0.26	0.30	0.30	0.30	0.29	0.29	0.30	0.29	0.30
2608	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2623	0.44	0.42	0.43	0.43	0.43	0.43	0.43	0.44	0.44	0.44	0.44	0.44	0.44	0.43
2659	0.30	0.28	0.29	0.28	0.29	0.29	0.29	0.30	0.30	0.30	0.31	0.30	0.29	0.29
3014	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3481	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00
4116	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4143	0.04	0.04	0.04	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
4720	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4728	0.08	0.08	0.09	0.09	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
5627	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6672	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.01
6685	0.17	0.16	0.16	0.17	0.17	0.16	0.17	0.17	0.17	0.17	0.16	0.16	0.17	0.17
7050	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7125	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Appendix 5C: Model Performance Evaluation Criteria Used for Calibration and Validation of the HEC-RAS model

Root mean square error (RMSE) = $\left[\frac{1}{n}\sum_{t=1}^{n}(Q_o^t - Q_s^t)^2\right]^{0.5}$

T-statistic = $\left[\frac{(n-1)(MBE)^2}{(RMSE)^2-(MBE)^2}\right]^{0.5}$

Observation standard deviation ratio (RSR) =$\frac{RMSE}{STDEV_{obs}} = \frac{\sqrt{\sum_{t=1}^{n}(Q_o^t-Q_s^t)^2}}{\sqrt{\left(\sum_{t=1}^{n}(Q_o^t-Q_m^t)\right)^2}}$

Percentage Bias = $\left[100 * \frac{\sum_{t=1}^{n}Q_o^t-\sum_{t=1}^{n}Q_s^t}{\sum_{t=1}^{n}Q_o^t}\right]$

Nash–Sutcliffe Efficiency Coefficient (NSEC) = $1 - \left[\frac{\sum_{t=1}^{n}(Q_o^t-Q_s^t)^2}{\left(\sum_{t=1}^{n}(Q_o^t-Q_m^t)\right)^2}\right]$

Performance	RSR	NSEC	PBIAS
Very good	$0 \leq RSR \leq 0.5$	$0.75 < NSEC \leq 1.0$	$PBIAS < \pm 0.10$
Good	$0.5 < RSR \leq 0.6$	$0.65 < NSEC \leq 0.75$	$\pm 0.1 \leq PBIAs < \pm 0.15$
Satisfactory	$0.6 < RSR \leq 0.7$	$0.5 < NSEC \leq 0.65$	$\pm 0.15 \leq PBIAS < \pm 0.25$
Unsatisfactory	$RSR > 0.7$	$NSEC \leq 0.5$	$PBIAs \geq \pm 0.25$

6

Chapter 6

Synthesis

6. Synthesis

6.1 Introduction

In developing countries like Ethiopia, investments in irrigated agriculture have been promoted as a viable strategy to achieve food security. In particular, expansion of small-scale irrigation (SSI) systems constitutes a major opportunity to eradicate poverty, as these systems offer significant advantages in cropping intensification, diversification and job creation. Although some studies argue that access to irrigation cannot be considered a panacea for alleviating poverty, there is a consensus on the potential of irrigation for increasing household income (Annys et al., 2021; Aurbacher and Abebe, 2019; Bacha et al., 2011; Beekma et al., 2021; Bekele and Mekonnen, 2021; Gebregziabher et al., 2009; Shikur, 2020; You et al., 2011). Despite mixed outcomes regarding the effect of SSI on poverty alleviation, investments in this area continue to be aggressively promoted, and they are expected to dominate the irrigated agricultural sector.

Nonetheless, the implications of SSI expansion for water resources and the performance of irrigated agriculture have gone largely unchecked and unregulated. One area that is often unregulated is the consequences of irrigation expansion on soil erosion and sediment yield. Conversion of lands into agricultural fields results in high sediment yield that jeopardises the functionality of irrigation schemes and causes them to underperform. Furthermore, excessive sedimentation brings about misuse of the investment in irrigated agriculture by increasing operation and maintenance costs, damaging infrastructure, and decreasing canal capacity, thus causing water scarcity. Sediment deposition alters the water management systems in the schemes and leads to the over-abstraction of water by damaging water control structures. In Ethiopia, water delivery in some schemes can be excessive, surpassing actual water demand by as much as sevenfold (Dejen et al., 2015).

However, despite the clearly identified role of sedimentation in causing underperformance and malfunction in irrigation schemes, the key elements that have contributed to sustaining some SSI schemes for many years remain unidentified. There is a lack of data and literature that help researchers to familiarise themselves with the extent of sedimentation problems and to investigate sediment-reducing options in irrigation schemes, and SSI schemes in particular. More specifically, information is barely available on the types, sources, and quantities of sedimentation that enter irrigation schemes, and on sediment management practices that are paramount to effectively reducing sedimentation problems.

Although many factors such as design and operational challenges aggravate the sedimentation problem, failure to account for overland sediment inflow continues to negatively alter the hydrodynamics of sediment transport. This is especially true in river diversion irrigation schemes with a longer feeder canal. Some previous studies have investigated the role of sediment in the design and operation of irrigation schemes (Munir, 2011; Nestore et al., 1998; Osman, 2015; Paudel et al., 2010; Theol et al., 2020b); however, these studies only focused on sediment influx from a river. The overarching objective of the current research was therefore to *assess the extent of sedimentation challenges, estimate their magnitude, and analyse how sedimentation problems might be overcome through the in-depth study of two SSI schemes in Ethiopia, using a socio-technical approach.* The conceptual framework that guided the research was presented in Figure 1.1 of Chapter 1.

This synthesis chapter discusses the main results of the research, returning to the four research questions raised in the respective analytical chapters (chapters 2–5). It presents the strengths and limitations of the current work, and extracts policy recommendations linked to the key research findings. It then concludes the thesis with reflections on the research approach and methods.

6.2 Discussion of the Main Results

6.2.1 Perspectives and Roles of Stakeholders in Sediment Management

Ensuring the sustainability of SSI schemes and effectively managing sedimentation problems requires the participation of various stakeholders who have an accurate overview of the problem. This section explores the factors that contribute, partially or completely, to sustaining irrigation schemes despite excessive sedimentation conditions, and draws conclusions based on case studies in two SSI schemes, Arata-Chufa (100 ha) and Ketar (430 ha). Although the investment returns and the efficiency of these schemes need further research, they can be considered to be performing well in terms of exceeding the number of beneficiaries and the command area size indicated in the design phase. The two irrigation schemes have been functioning for more than three decades. Even though their infrastructure has deteriorated, both schemes are thriving in terms of command area size, registering an increase of 17% for the Arata-Chufa scheme and 14% for the Ketar scheme.

Chapter 2 of this thesis investigated how various stakeholders perceive sedimentation problems and the drivers of sedimentation. The findings indicate that the stakeholders perceive sedimentation as a severe problem, although they have varying perceptions about the drivers of the sedimentation. According to farmers, the main drivers of sedimentation were internal factors, like design and operation and management (O&M) challenges. Engineers, however, attributed excessive sedimentation mainly to external factors such as soil erosion. These findings support the works of (Amede, 2015; Awulachew and Ayana, 2011) which reported design failures, poor water management practices, and watershed degradation problems as major causes for underperformance in most of the irrigation schemes.

This thesis also sought to understand factors contributing to sustain satisfactory SSI scheme performance, despite problems of excessive sedimentation – thus potentially pointing to best practices. Key factors found to sustain SSI schemes were having a well-organised institution trusted by its members and building on stakeholders' interests to sustain participation in sediment management. In each of the two schemes, farmers were found to have restructured the institutional set-up of their water users' association (WUA) and combined it with their local institutions. Moreover, the farmers exhibited keen interest in their scheme, which stimulated them to commit extra hours to manage sedimentation during desilting campaigns. Every farmer was aware of the economic benefits provided by their access to irrigation, and this was expressed in their high participation in every desilting campaign organized. Furthermore, the two irrigation schemes had been built as an upgrade of pre-existing farmer-manged irrigation systems, in response to a request from farmers. This request and farmers' maintenance of the pre-existing system are additional indicators of farmers' interest. Thus, lack of interest, which has often been reported as a cause of irrigation system underperformance, does not appear to have been an issue here. Farmers' commitment to making the collective desilting campaigns a success also led to their acquiescence to a system for conflict resolution involving in-cash or in-kind sanctions, including possible deprivation of water use rights.

The issues of lack of participation and weak institutions are commonly reported as undermining the performance and even the functionality of irrigation schemes (Amede, 2015; Yami, 2013). The findings from Chapter 2 align with the conclusions of earlier studies, though in the case study schemes, sufficient participation and robust local institutions contributed to sustain satisfactory SSI performance.

6.2.2 Sedimentation from the River: Quantities and Management in SSI Schemes

The sediment influx to an irrigation scheme greatly induced by the design approaches of the scheme, the location of the intake and the command area. For example, the catchment of the Ketar scheme is characterised by steep topography; thus, the scheme was designed with a long feeder canal (some 5 km) to compensate for the elevation difference between the intake and field plots. Having a long feeder canal subjected the Ketar scheme to sedimentation from an overland flow in addition to river sediment, while the Arata-Chufa scheme, which has a shorter feeder canal (600 m), is affected mainly by river sediment. In both schemes, irrigation is practiced from September to May, after which the farmers switch to rainfed agriculture. The intake is closed during the rainy season (June to August); thus, the sediment inflow to canals comes mainly from an overland sediment course. However, there is little data to quantify the relative contribution of river and overland flow sediment in the SSI schemes. Notably, sediment data was missing in SSI schemes, although other data was possibly retrieved from previous studies and design documents.

In such data-scarce and resource-scarce conditions, participatory research offers a potentially valuable tool to obtain information for environmental resource planning (Debolini et al., 2013; Drazkiewicz et al., 2015; Oliver et al., 2012; Ritzema et al., 2010). The current research applied participatory methods in an effort to benefit from local knowledge, in order to fill in the data gap. Specifically, this study used a participatory measurement exercise to quantify the contributions of river and overland sediment in SSI schemes, combined with monitoring farmer-led desilting campaigns and soil erosion modelling spanning three years, from 2016 to 2018. The findings, presented in Chapter 3, indicate that river sediment contributed more than 90% of sedimentation in the Arata-Chufa scheme and less than 50% in the Ketar scheme. This finding has wider implications, as it indicates the importance of looking beyond just the hydrodynamics of water and sediment transport in the canal when conducting research on sediment transport in irrigation structures. Rather, sediment sources should be identified and quantified by analysing the sediment budget in a canal before advancing to hydrodynamic model simulations. Physical inspection of the main canal to discern the potential for overland sediment inflow is an important first step in such an investigation.

Indeed, both schemes exhibited excessive sedimentation, ranging from 0.32 m^3/m/year (2017) at Arata-Chufa to 1.11 m^3/m/year (2017) at the Ketar scheme. Problems of water undersupply and canal capacity reduction were reported as occurring just one to three months into the new irrigation season. However, where the main source of excessive sedimentation was overland flow – the Ketar scheme – conducting desilting campaigns annually after the rainy season was found to be adequate. Belaud and Baume (2002) tested the periodicity of desilting campaigns from one to three years, and found that removing sediment every year was ideal for system maintenance and performance. Despite this, in the schemes studied in the current research, desilting campaigns could not be delayed to the end of the irrigation season, as the main canal usually silted up completely. Hence, the main message of Chapter 3 is that the basis for optimising the frequency of desilting campaigns, and for tackling sedimentation problems in general, lies in knowing the sources and quantity of sedimentation.

6.2.3 Sedimentation from the Overland: Quantities and Severity in SSI Schemes

The most striking finding of Chapter 3 is that the sedimentation in the two schemes does not originate entirely from the river source. It was observed that the annual sediment load in the Ketar scheme (2522 m^3 in 2018) was much higher than the sediment influx from the river (1741 m^3 in 2018). This was evidenced by the comparison of the sediment removed during the desilting campaigns with the measurement of sediment load from the river. Moreover, it was observed that the schemes were subjected to overland sediment influx. Thus, the contribution of overland sediment inflow cannot be neglected, and studies to reduce sedimentation problems are incomplete without addressing the topic. Hence, this thesis estimated the overland sediment to illustrate its contribution and severity in an irrigation scheme. To model the soil loss and the sediment yield to the schemes, the current thesis used a less data-intensive and more common approach – the revised universal soil loss equation (RUSLE). Although the estimate of mean annual soil loss presented in Chapter 4 of this thesis (18.5 t/ha/yr for Ketar) is lower than the figures estimated by other studies (27.5 to 84 t/ha/yr) (Gelagay and Minale, 2016; Haregeweyn et al., 2015; Haregeweyn et al., 2017; Sonneveld et al., 2011), the contribution of overland flow to canal sedimentation (2042 m^3 in 2018 in the Ketar scheme) is still significant and cannot be overlooked.

Overland sediment inflow differed significantly between the two schemes, due mainly to the different lengths of the respective feeder canals. The feeder canal of the Ketar scheme is some 5000 m long, about eight times the length of the Arata-Chufa scheme; however, the overland sediment influx at the Ketar scheme is 255 times that of the Arata-Chufa. At the Ketar scheme, a ridge formed by sediment previously dredged (2720 m^3 in 2016 and 2690 m^3 in 2017) from the hotspot section of the main canal (2,433 m) served as a makeshift barrier that protected the canal from overland flow, effectively reducing the catchment area from 1,082 ha to 215 ha. Without this ridge, the overland sediment inflow could have been much higher. This finding demonstrates that neglecting overland sediment inflows, particularly for gravity-type irrigation schemes with long feeder canals transiting areas prone to soil erosion, is likely to result in inadequate and unsustainable interventions to manage excessive sedimentation. The outputs of the RUSLE model were later used in a hydrodynamic model to investigate measures to reduce sedimentation problems in the irrigation schemes.

6.2.4 Options for Reducing Sedimentation Problems in SSI Schemes

Irrigation canals are designed with the assumption of uniform and steady flow. Hence, the likelihood irrigation canal responding to a flexible and varying water demand with sediment conditions is minimal. Many of the proposed operational options for reducing sedimentation problems are based on explicit knowledge of sediment and water transport, which many irrigation engineers lack, particularly in developing countries. The role of sediment in reducing the canal capacity due to bed aggradation has been neglected or less emphasised. Desilting campaigns in many irrigation schemes are mainly organised at the end of the irrigation season; however, the water demand at the end of the season was computed under the assumption that there would be no bed change at the end of the season.

Sedimentation must be reduced from its sources to fundamentally tackle the problems in irrigation schemes by addressing soil erosion challenges and the consequent sediment yield. However, two options are available which can potentially reduce sedimentation problems: (i) design modification and/or (ii) operational change. To reduce sedimentation, this thesis tested the effectiveness of three design parameter modifications (canal lining, construction of a new settling basin, and increasing longitudinal bed slope) as well as one operational change (sediment flushing during the rainy season). The findings of this investigation were presented in Chapter 5.

In brief, sediment flushing during the rainy season (closure season) from June to August was found to be the most promising low-cost option to reduce sedimentation in both schemes. The second-best option was lining the alluvial part of the main canals, particularly for a scheme mainly experiencing river sediment. Construction of a new settling basin combined with canal flushing was also a promising option; though the high construction cost of the basin was thought to hinder implementation of this solution in SSI schemes. Increasing the longitudinal bed slope produced insignificant sediment reduction in both schemes. This implies that low-cost options to reduce sedimentation should focus on operational changes rather than design modifications.

Some of these findings are remarkable, while others align with the outcomes of the few previous studies available. For example, the results regarding the operational change (flushing of sediment), particularly for the Ketar scheme, are close to those of Theol et al. (2019) and Osman et al. (2017). Theol et al. (2019) found that some 54% of sediment deposition could be reduced by intermittently fully opening and closing the gate. Osman et al. (2017) found that a 48% reduction in sediment could be achieved by reducing inflow by 51% during high sediment concentration periods. The current study found that sediment deposition could be reduced by 57% by flushing sediment from the canal during the rainy season, particularly for the Ketar scheme. The result of flushing for the Arata-Chufa scheme was remarkably higher, as flushing here removed more than 80% of the deposited sediment.

6.3 Overall Key Research Findings and Limitations

This thesis explored the challenges posed by sedimentation in SSI schemes in an erosion-prone developing country. Particularly, it investigated the perspectives of stakeholders on sediment management and the roles stakeholders played in managing excessive sedimentation in SSI schemes, while also identifying the sources of sedimentation, quantifying the magnitude of sedimentation and developing options for reducing sedimentation. Chapter 2 found that farmers and engineers had different perceptions of the drivers of sedimentation, and that farmers' willingness to contribute their labour was key to sustaining SSI schemes.

This thesis distinguishes itself from previous studies on the role of sediment in irrigation schemes by the following major contributions. First, it discovered that informal and well-organised local knowledge and institutions are superior to the blue-print institutions for managing severe sedimentation problems in SSI schemes. Second, it demonstrated that the basis for tackling sedimentation problems in SSI schemes lies in identifying the sources of sedimentation. Third, it revealed that overland sediment contributes significantly to sedimentation in some schemes, and that neglecting it alters the hydrodynamics of sediment transport in irrigation canals which is crucial for developing options to overcome sedimentation problems. Fourth, the current thesis coupled a hydrodynamic sediment model with an erosion model to develop options to reduce both river and overland flow sediment. Finally, it revealed that operational change is a more promising option than design modification for countering problems of excessive sedimentation in existing SSI schemes that are experiencing both river and overland flow sediment.

This research has substantial societal relevance, as it advances understanding of a major underperformance issue (sedimentation) affecting SSI schemes, while SSI schemes can make a key contribution to tackling challenges of poverty and food insecurity. At the local and regional level, the findings presented in this thesis can be applied to reduce operation and maintenance costs and the number of days farmers must invest in sediment management activities.

This thesis answered the four research questions to a considerable extent presented in Chapter 1. However, due to Covid-19 travel restrictions, the research question 4 was modified from participatory modelling to the conventional hydrodynamic model, where only one scenario proposed by farmers (canal lining) was used. Initially, the plan was to discuss the results on research questions 2, 3 and 4 with stakeholders and perform participatory modelling with stakeholders. The aim in doing so was to integrate local tacit knowledge with explicit scientific knowledge for development of actionable knowledge for sedimentation management in SSI schemes. Although the findings demonstrate farmers' use of local institutions to manage sedimentation problems (Chapter 2), the research was unsuccessful in integrating the two types of knowledge. Hence, an recommended avenue for future research is to develop a structure whereby local institutions can be integrated with formal knowledge sources to improve sediment and water management in irrigation schemes.

The current study also attempted to use a hydrodynamic sediment model tailored to the irrigation canals; that is, the Simulation of Irrigation Canals (SIC) model (Baume et al., 2005). Unfortunately, the application of the SIC model to the irrigation schemes was unsuccessful, due to the instability of the model while calculating unsteady supercritical flows (Haijue and Yuchuan, 2008; Simons et al., 2000). However, this thesis showed that the HEC-RAS river model can be successfully applied to analyse the role of design and operational modification on sediment transport in small-scale irrigation schemes. This study did not, however, account for the effects on sediment transport of weed growth in the canal, canal width to water depth (B/h) ratio, side slope, and irregularity of canal geometry and roughness, particularly in the Ketar scheme. Future research could also focus on the instability challenges of sediment models dedicated to irrigation canals and participatory sediment modelling, particularly in small-scale irrigation.

This thesis analysed the uncertainty of the HEC-RAS model by performing 1 hr to 24 hr computational time steps for numerical parameter sensitivity and analysed Manning roughness for physical parameters sensitivity. However, the HEC-RAS model is also sensitive to other parameters such as cross-sectional spacing and stability factors. Moreover, the RUSLE model was used to compute overland sediment yield into the schemes. High uncertainties in the RUSLE model were minimised by collecting field data for verification. Future research could use more parameters and methods such as a physically-based distributed model like the Soil and Water Assessment Tool (SWAT) to reduce uncertainties for a more accurate estimation of sedimentation.

This thesis showed that flushing the sediment during the rainy season seems a promising low-cost option to reduce sedimentation problems from a hydrodynamic point of view. Future research, however, could explore users' perceptions and their willingness to implement it from an operational point of view. This thesis furthermore found that sedimentation caused a gradual reduction of canal capacity. However, it did not investigate the actual implications of canal capacity reduction for water productivity and yield gap. To this end, future research could link a crop model to an irrigation canal model to explicitly investigate the impact of sedimentation on crop production. As water and sediment transport are inextricable components of canal hydrodynamics, insight could be gained into the impact of agricultural water management on sedimentation. For example, deficit irrigation and improved irrigation scheduling are good options to improve water management without causing reductions in yield. Future research could investigate the effects of these types of agricultural water management practices on sedimentation.

Despite the limitations discussed above, this thesis play a major part in tackling sedimentation challenges in irrigated agriculture, particularly in SSI schemes. The thesis serves as a stepping stone to future studies focussing on sedimentation in irrigation schemes, particularly those combining river and overland flow sediment. Moreover, the section below interlinks the key findings with policy recommendations for policymakers.

6.4 Policy Implication

Food security and poverty eradication require robust and proactive agricultural policy. However, in many countries, the agrarian sector is governed by policies geared mainly towards maintaining rural livelihoods and keeping food prices under control (Beekma et al., 2021). Though access to irrigation can contribute to alleviating poverty, for the agricultural sector to flourish, synergies are needed between enabling agricultural policies and policies in other sectors affecting rural areas.

In Ethiopia, agricultural policy long overlooked irrigated agriculture as a priority for smallholders, stimulating rainfed agriculture instead (Bacha et al., 2011). Since 1991, the government has promoted irrigation expansion, including rapid expansion of irrigation infrastructure at the local level (Bekele and Mekonnen, 2021). However, the current irrigation water policies, strategies, and guidelines were formulated as development-oriented towards achieving the national socioeconomic target (Bekele and Mekonnen, 2021). Yet, many of the operationalised irrigation schemes in the country have failed to achieve the desired objectives (Dejen et al., 2015; Amede, 2015; Awulachew and Ayana, 2011; Makombe et al., 2017). Policy reform must be geared towards ensuring higher efficiency of irrigation systems, old and new. Moreover, strategies and policies need to address post-irrigation development challenges, such as sedimentation problems and environmental threats caused by irrigation expansion.

This thesis promotes policy reforms and recommendations related to overcoming sedimentation problems in SSI schemes. Chapter 2 revealed that a lack of local capacity and technology appropriation, the process by which users make technologies their own to assume responsibility for managing sedimentation, were major barriers to SSI scheme sustainability. For example, in the Arata-Chufa scheme, the farmers were unable to dredge the sediment from the pond that serves 60% of the command area due to their lack of machinery. Therefore, strong technical and technological support, supported by appropriate policies, is needed to develop the capacity of farmers and irrigation institutions at the local level and help them to sustain irrigation schemes.

The current thesis revealed that the irrigation schemes experienced significant sedimentation problems. Sedimentation problems partly originated from expansion of irrigated agriculture. Policy instruments are needed to control soil loss, at least from irrigated agricultural lands, to tackle underperformance issues in irrigation schemes due to sedimentation problems.

Another issue that would benefit from policy attention is the informal expansion of irrigation lands beyond their design capacity, leading to over-abstraction of irrigation water, as sediment inflow is dependent on the quantity of water abstracted. The two irrigation schemes studied in the current research had both undergone downstream expansion. This had caused over-abstraction of water and even jeopardized sediment management practices due to a conflict arising between member and non-member downstream farmers. A formal expansion could help to overcome adverse impacts of new irrigation schemes, such as construction costs and time and soil loss (de Fraiture and Giordano, 2014). Nonetheless, informal expansion leads to water scarcity problems in the irrigated system (de Fraiture and Giordano, 2014). Therefore, to sustain SSI schemes, strong policy instruments are needed to avoid the challenges posed by downstream expansion.

In order to counter the problems discussed above, this thesis puts forward four policy recommendations to overcome excessive sedimentation challenges in irrigated agriculture. First, data and knowledge gaps should be filled by encouraging the use of local knowledge, institutions, and participation. Second, the sources of sedimentation in the irrigation scheme must be identified, as this is the basis for developing options to reduce sedimentation. Since there are two sources of sedimentation, two different approaches to tackling it will be called for. Third, sediment management that focusses only on the canal system should be expanded towards catchment management. In schemes where overland sediment inflow is considerable, focussing on protecting the canal from overland flow sediment will make it possible to significantly reduce sedimentation. Fourth, low-cost approaches to reduce sedimentation in existing schemes should focus on operational changes rather than design modifications. Many SSI irrigation schemes have been designed based on expensive frequent desilting campaigns as an option to manage sedimentation problems. However, peak discharges during the rainy season could be used for flushing the deposited sediment without incurring costs. It should be noted that such an option might require the construction of auxiliary structures to facilitate the flushing activity back to the river in some schemes, and its implementation is subject to further analysis.

6.5 Reflection on Research Approach and Methods

The presented research examined the sedimentation problems experienced in SSI schemes, testing two main hypotheses. The first was that participation of local users and combining scientific findings with local tacit knowledge is a promising approach to co-generate actionable knowledge in order to overcome data scarcity challenges and enhance understanding of sedimentation problems in developing countries. The second hypothesis was that by modifying design parameters and changing operating practices, sedimentation problems can be reduced in existing irrigation schemes. The overarching research question was, "*What is the extent of the sedimentation problem, and how can it be addressed and the overall performance of small-scale irrigation schemes enhanced employing a socio-technical study?*"

The thesis found that indeed sediment problems were severe in the studied SSI schemes. However, operational solutions, such as flushing the sediment during the rainy season, appear to offer a promising approach to reduce sedimentation. To reach this conclusion, the current study used a socio-technical approach combined with participatory action and planning (Goss, 2004) and modelling. This included a participatory monitoring and data-gathering exercise to measure and analyse sedimentation data for three years (2016 to 2018), semi-structured interviews with 100 subjects, soil erosion modelling with RUSLE and hydrodynamic sediment modelling with HEC-RAS. Widening the scope of the employed participatory action and planning tools could lead to a yet better understanding of stakeholders' perceptions of sedimentation problems and their roles in sedimentation management, perhaps pointing towards new paths for tackling the issue.

In addition to the hydrodynamic sediment model, use of laboratory physical models to test the scenarios can be useful to reduce the uncertainty of the sediment model by triangulating the result. This thesis used the sediment model to analyse the role of design modification on sedimentation in existing SSI schemes. However, the sediment models are a robust tools to analyse the effect of various irrigation canal design approaches on sedimentation to arrive at better irrigation canal design approach for sediment reduction point of view. In short, the overarching message of the this study is that the current design and operation practice need revision for increasing sediment management in irrigation schemes.

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A

Appendices

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Summary

Expansion of irrigated agriculture, particularly small-scale irrigation (SSI), is promoted as a pathway to maintain food security and eradicate poverty in developing countries. However, most irrigation schemes underperform, and the expected returns on investment seldom materialize. Excessive sedimentation is a major problem hindering irrigation schemes from operating at full capacity. As various stakeholders are involved in the implementation and management of SSI schemes, understanding their roles and perceptions of sedimentation problems is crucial to improve sediment management. In most SSI schemes, however, data scarcity represents a critical obstacle to understanding and improving irrigation performance, particularly in developing countries such as Ethiopia. The large majority of SSI schemes in Ethiopia receive sediment from overland erosion flows, though this source of sedimentation has been largely overlooked in previous studies. Research has focused mainly on sediment influx from river sources. Neglecting overland sources of sedimentation has resulted in an incomplete picture of canal sediment hydrodynamics.

The current thesis seeks to fill this research gap. It explores stakeholders' views and roles in sediment management, identifies and quantifies sedimentation sources, and analyses options for reducing sedimentation. It does so with a focus on two SSI schemes in Ethiopia: Arata-Chufa (100 ha) and Ketar (430 ha). It poses four specific research questions, which are answered sequentially in chapters 2 through 5.

Chapter 2 analyses stakeholders' roles and perspectives on sedimentation management in SSI schemes. The chapter explores the views of engineers as well as farmers and of upstream, midstream and downstream farmers on the sedimentation problems affecting their SSI schemes. It furthermore investigates how these SSI schemes have continued to perform relatively well over decades of use, despite experiencing problems of excessive sedimentation. The research deployed a participatory rapid diagnosis and action planning approach, consisting of a literature review, a participatory rural appraisal and semi-structured interviews of 100 subjects, to analyse the roles and perceptions of stakeholders on sediment management. Results indicate that engineers and farmers had differing opinions of the drivers of sedimentation. Farmers reported design problems and poor operation and maintenance, while the interviewed engineers indicated erosion and irrigation technologies as the main causes of excessive sedimentation. The main message of Chapter 2 is that well-organized local institutions and extra time devoted by farmers to sedimentation management tasks are vital to SSI sustainability. However, data was lacking to quantify the extent of the sedimentation problems in the studied schemes.

Chapter 3 presents a participatory monitoring exercise set up to tackle the knowledge and information gap regarding the type and sources of sediment entering the SSI schemes. Apart from overcoming data scarcity challenges, measuring the annual sediment load and assessing local desilting campaigns secured the data needed for a hydrodynamic model to analyse options for sediment reduction. As rivers in Ethiopia carry huge sediment loads, enormous amounts of

sediment were brought into the studied schemes, ranging from 220 m^3 for the Arata-Chufa scheme to 1,741 m^3 for the Ketar scheme. A canal sediment budget analysis indicated that up to 95% of the sedimentation in the Arata-Chufa canal came from the river source, compared to 46% for Ketar. Farmers cleared 163 m^3 of sediment annually from the Arata-Chufa canal; while Ketar farmers cleared 2,522 m^3 annually. These measurements indicate that the schemes experienced substantial sediment influx from overland flow, in addition to the sediment conveyed into the schemes with river water.

Many irrigation schemes, particularly those with long headrace canals, are exposed to the risk of overland sediment inflow. This risk is heightened by high rates of soil erosion in the surrounding catchment and the absence of structural measures to protect the main canal from overland erosion inflows. Chapter 4 computes sediment influx from overland flow using the revised universal soil loss equation (RUSLE) model, an empirical erosion model recognized as a standard method to calculate the average risk of erosion. The RUSLE results indicate that the annual sediment yield from overland flow was about 8 m^3 for Arata-Chufa and 2,042 m^3 for the Ketar scheme. These figures were used as boundary conditions in the hydrodynamic model.

Hydrodynamic sediment models are a robust tool to analyse various scenarios or options for sediment reduction. Chapter 5 uses the open-source one-dimensional (1D) Hydrologic Engineering Centre's (HEC) River Analysis System (HEC-RAS) 6.0 model to analyse options for reducing sedimentation in the SSI schemes. As both design and operational challenges can aggravate problems of excessive sedimentation in irrigation schemes, four scenarios were formulated, representing modifications in design and/or operation. These scenarios were (1) lining the canal with concrete, (2) constructing a new settling basin (with or without flushing), (3) increasing the longitudinal bed slope and (4) sediment flushing during the rainy season.

The results of the HEC-RAS model indicate that sediment flushing during the rainy season is the most promising alternative for reducing sediment deposition in both schemes. Flushing would remove more than 80% of the deposited sediment from the Arata-Chufa scheme and more than 50% from the Ketar scheme. The second-best option is lining the alluvial part of the canal. This would be particularly effective in the Arata-Chufa scheme, as sediment there mainly originates from the river. Lining the Arata-Chufa canal could reduce sediment deposition by some 28%. These two options are especially promising because of the low costs involved. Building a new settling basin with a flushing option would yield a greater sediment reduction than lining the canal; however, the huge costs involved constitute a substantial barrier to implementation of this option.

Increasing the longitudinal bed slope of the canal would only reduce sedimentation to a limited extent in the existing schemes. This is because modifying one design parameter alone does not produce a sediment transport capacity high enough to convey the incoming sediment load. A combination of design modifications, for instance, in roughness and bed slope, could help 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 the operational stage in existing schemes is impractical and would incur enormous cost. In conclusion, low-cost options to reduce sedimentation problems are more likely to be found in operational measures, rather than design modifications.

The findings of the current thesis are of utmost societal relevance, as increasing the performance of SSI schemes is key to maintaining food security in many developing countries, and sedimentation is a key challenge in SSI scheme performance. The main findings of this research can be applied at the local and regional level to improve sediment management in irrigated agriculture, and at the national level to guide new policy instruments. This thesis furthermore advances the sparse literature in the field of irrigation canal sedimentation, particularly with respect to SSI schemes. First, it demonstrates the role of local knowledge and participation in the successful management of SSI schemes. Second, it reveals that sedimentation in SSI schemes originates from different sources, and that accurate quantification of the contributions of these sources is necessary in order to effectively tackle sedimentation. Third, it couples an erosion model with a hydrodynamic model to comprehensively analyse sedimentation in irrigation canals. Fourth, modelling findings indicate that changing operational practices may offer a low-cost option for reducing excessive sedimentation in irrigation canals, making expensive design modification unnecessary in many cases.

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Zerihun Gurmu
August 2022
Wageningen, The Netherlands

Short biography

Zerihun Anbesa Gurmu was born in Arsi (Bekoji), in Oromia Regional State, Ethiopia. Zerihun attended elementary and high school (from grade one to grade ten) in Bekoji and attended grades eleven and twelve at Hawas Preparatory School in Adama, Ethiopia. He graduated from Arba Minch University in 2008 with a bachelor's degree in Water Resources and Irrigation Engineering. Zerihun obtained a Master's degree in Hydrology and Water Resources Management in 2010 from Arba Minch University. He worked at Arba Minch University as a graduate assistant (2008 to 2010), lecturer and researcher (2010 to 2016), head of the Water Resources and Irrigation Engineering Department (2011 to 2013), and research coordination officer of the Institute of Technology (2013 to 2016). He started his PhD in 2016 at the Water Resources Management Group of Wageningen University & Research, The Netherlands. His PhD project mainly focused on sedimentation challenges in small-scale irrigation schemes. Zerihun has expertise in socio-technical research methods; sediment transport and modeling; hydrology and water resources management; climate change and land use analysis; irrigation engineering; catchment and river modeling.

List of publications

Gurmu, Z. A., Ritzema, H., de Fraiture, C., & Ayana, M. (2019). Stakeholder Roles and Perspectives on Sedimentation Management in Small-Scale Irrigation Schemes in Ethiopia. *Sustainability, 11*(21), 6121. doi:10.3390/su11216121

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Gurmu, Z. A., Ritzema, H. P., Fraiture, d. C. M. S., & Ayana, M. Hydrodynamic Modeling to Develop Design and Operational Options for Sedimentation Reduction in Small-Scale Irrigation Schemes, Ethiopia. Journal of Hydrology: Regional Studies (under review).

Conferences

SENSE Symposium, 2 June 2022, Wageningen University & Research, Wageningen, The Netherlands.

20th International Symposium on Sustainable Water Resources Development, 10-11 June, 2022, Arba Minch University, Arba Minch, Ethiopia.

Netherlands Earth and Environmental Science Congress (NAC 2022), 5-6 September, 2022, Utrecht, The Netherlands.

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born on 29th October 1985 in Arsi, Ethiopia

has successfully fulfilled all requirements of the
educational PhD programme of SENSE.

Wageningen, 20th September 2022

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The SENSE Research School declares that **Zerihun Anbesa Gurmu** has successfully fulfilled all requirements of the educational PhD programme of SENSE with a work load of 34.1 EC, including the following activities:

SENSE PhD Courses

- Environmental research in context (2016)
- Research in context activity: 'Hosting and co-hosting the annual symposium on "sustainable water resources development" as part of research context activity' (2022)

Other PhD and Advanced MSc Courses

- Sediment transport in irrigation canal , IHE Delft (2016)
- Information Literacy for PhD including EndNote introduction, Wageningen Graduate Schools (2016)
- Making an Impact: How to increase the societal relevance of your PhD research, Wageningen Graduate Schools (2016)
- The essential of scientific writing and presenting, Wageningen Graduate Schools (2019)
- Scientific publishing, Wageningen Graduate Schools (2019)
- Reviewing a scientific paper, Wageningen Graduate Schools (2019)
- Scientific artwork - vector graphics and images, Wageningen Graduate Schools (2019)
- Project and Time Management , Wageningen Graduate Schools (2019)
- Brain training, Wageningen Graduate Schools (2019)
- Adobe InDesign , Wageningen Graduate Schools (2019)
- Career perspective, Wageningen Graduate Schools (2019)
- An Introduction to (La)TeX, Wageningen Graduate Schools (2019)
- Water policy and politics, Wageningen School of Social Sciences (2022)

Management and Didactic Skills Training

- Supervising BSc student with thesis entitled 'Erosion risk and sediment movement on the slopes above the main canal of Ketar 1: Applying the RUSLE model in Oromia region, Ethiopia' (2018)

Oral Presentation

- *Prospects and challenges of sedimentation in irrigated agriculture in Ethiopia*. 20th International Symposium on Sustainable Water Resources Development, 10 June 2022, Arba Minch, Ethiopia
- *Irrigated agriculture and sediments: perception, severity, and options for reduction*. NAC Conference, 5-6 September 2022

SENSE coordinator PhD education

Dr. ir. Peter Vermeulen

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Cover photo	Arata-Chufa intake (front), Ketar farmers in desilting campaign (back)