Understanding Sedimentation Trajectories and Social Relations with Agent-based Modeling of Sudan's Gezira Scheme

Eunice Koid

Delft University of Technology

MSc. Civil Engineering Thesis, 2022

Eunice Koid (5278023)
Understanding Sedimentation Trajectories and Social Relations with Agent-based Modeling of Sudan's Gezira Scheme (2022)

The work in this thesis was made at the:

Faculty of Civil Engineering and Geosciences
Stevinweg 1
2628 CN Delft
Delft University of Technology

Thesis Committee:
Maurits Ertsen (Chair)
Tabitha Kabora
Bram van Prooijen
Ronald van Nooyen

Keywords: Gezira, sedimentation, maintenance, agent-based modeling, irrigation canals

Executive Summary

In the 1920s, British colonists built one of the largest irrigation systems in the world - the Gezira Scheme in Sudan. Meticulously designed, it was seen as a symbol of power and planned development that advanced the British colonial economy. However, by the end of the 20^{th} century, it became a symbol of failed development as its function deteriorated due to sedimentation. Scholars have argued about the causes of sedimentation, claiming that the canals' deterioration was caused by the transition of maintenance responsibilities from centralized maintenance by the British colonists to ad hoc maintenance by the Sudanese tenants. Without systematic historical measurements, sedimentation must be further studied to validate these claims.

The Gezira Sedimentation Agent-based Model (GSAB Model) simulates the trajectory of sediment deposition in the minor canals under different environmental conditions and maintenance strategies. Nine scenarios were simulated over 100 years: centralized maintenance (SIM-1), ad hoc maintenance (SIM-2), increased sediment concentration with centralized maintenance (SIM-3), increased sediment concentration with ad hoc maintenance (SIM-4), increased sediment concentration with reduced ad hoc maintenance capacity (SIM-4.5), inadequate maintenance in major canal with centralized maintenance (SIM-5), inadequate maintenance in the major canal with ad hoc maintenance (SIM-6), increased inflow from the major canal with centralized maintenance (SIM-7), and increased inflow from the major canal with ad hoc maintenance (SIM-8).

Results of the GSAB Model scenario analyses confirm that sedimentation has been a major issue since the Gezira Scheme officially opened in 1925. The outcome of the baseline scenario with centralized maintenance (SIM-1) suggests that even with the ideal Lacey's regime theory canal design and full capacity of centralized maintenance, the minor canals are still 69% filled with sediment. The result of the baseline scenario simulation with ad hoc maintenance (SIM-2) shows slightly less net sediment deposition in the minor canals at approximately 67% of the full minor canal volume. These results do not support the claim that the management change from centralized to ad hoc maintenance was the main contributing factor to worsening sedimentation in the Gezira canals. Conversely, the GSAB Model's results indicate that ad hoc maintenance performs better than centralized maintenance even at lower capacities. Though the exact capacity of tenants throughout Gezira's history is uncertain, the model's results present evidence that the principle of ad hoc maintenance is adequate for maintaining a steady level of sediment removal. While higher incoming water flow rates contribute minimally to sedimentation in the minor canals, an increased sediment concentration due to erosion from upstream areas poses the biggest threat to sedimentation. In the GSAB Model, centralized maintenance could not effectively mitigate the impact of higher sediment loads, unlike ad hoc maintenance. Because of the infrequency of its biennial, off-season schedule, centralized maintenance has little flexibility to adjust is capacity to remove excess sediment. As a result, the minor canals become clogged. On the other hand, ad hoc maintenance has better adaptability; it can be conducted throughout the year and in any given year. Furthermore, it can be initiated early so that excess sediment from higher sediment loads does not accumulate in the minor canals.

The GSAB Model provides a tool for reconstructing potential historical sedimentation trajectories and disentangling common social narratives about the causes of sedimentation. In addition, the model's results illuminate potential areas for management to consider when addressing the sedimentation issue in the minor canals. For instance, management could focus on four aspects: refining the canal design, improving the function of flow control structures, reducing the incoming sediment load, and adjusting maintenance efforts so that the water supply is not disrupted.

Contents

Acronyms

ABM Agent-based model(ing). 3, 4, 7, 20–22, 24, 98, 99, 101

EMC Earthmoving Corporation. 16, 45

GSAB Model Gezira Sedimentation Agent-based Model. ii, iii, 4, 6, 23, 32–34, 36, 37, 42–49, 52, 56, 58, 62–67, 69, 71–74, 80, 83, 85–87, 89–96, 98, 100–102

HRS Hydraulic Research Station. 16

IWC Irrigation Water Corporation. 16

MOIWR Ministry of Irrigation and Water Resources. 15, 16

O&M Operations and Maintenance. 3, 9, 16, 98, 101, 102

ODD Overview, Design Concepts, and Details. 23, 30

SGB Sudan Gezira Board. 9, 15, 16, 95

SPS Sudan Plantation Syndicate. 15

WUA Water User Association. 16, 49, 98, 99, 102

Nomenclature

ρ_s	Dry sediment density (kg/m^3)
ρ_w	Density of water (kg/m^3)
τ_b	Bed shear stress (N/m^2)
τ_d	Critical shear stress for deposition (N/m^2)
τ_e	Critical shear stress for erosion (N/m^2)
A	Cross-sectional area (m^2)
b	Bed width (m)
C	Chezy coefficient ($m^{0.5}/s$)
c_s	Sediment concentration (kg/m^3)
cap_a	Capacity of tenants to conduct ad hoc maintenance (%)
cap_c	Capacity of centralized management to conduct maintenance (%)
D	Deposition flux ($kg/m^2/s$)
E	Erosion flux ($kg/m^2/s$)
h	Water depth (m)
h_s	Sediment depth (m)
$h_{s,\%}$	% of the max sediment depth that triggers ad hoc maintenance (%)
K_a	Lacey equation constant for cross-sectional area (-)
K_p	Lacey equation constant for wetted perimeter (-)
K_s	Lacey equation constant for bed slope (-)
M	Erosion rate ($kg/m^2/s$)
m	Side slope of a trapezoidal channel (-)

n	Manning's roughness coefficient ($s/m^{1/3}$)
$o_{\%}$	Offtake proportion (%)
P	Wetted perimeter (m)
Q	Water discharge (m^3/s)
Q_s	Sediment discharge (m^3/s)
R	Hydraulic radius (m)
S_0	Bed slope (cm/km or dimensionless)
S_f	Energy slope (-)
$u*$	Shear velocity (m/s)
U	Water velocity (m/s)
V_s	Volume of sediment (m^3)
$V_{max,minor}$	Max volume of the minor canals, up to the design water level (m^3)
w_s	Settling velocity (m/s)

Chapter 1

Introduction

In the early 1900s, British land surveyors began to measure land on the Gezira plain in Sudan with hopes of developing it for their country's own economic interests. The British government saw Gezira as an opportunity to use the Blue Nile for gravity irrigation of crops. By 1925, the Gezira Irrigation Scheme, as it is known today, was officially opened. Spanning 880,000 hectares today, it still stands as one of the largest irrigation systems in the world (Osman, 2015). This irrigation scheme not only advanced the British colonial economy through cotton exports but also became a symbol of power and control (Ertsen, 2016a). Yet, despite this image of power and claims by British engineers that the Gezira Scheme was perfectly executed according to plan, the Gezira Scheme became "a symbol of failed development" and an instrument of British colonial oppression by the end of the 20^{th} century (Bernal, 1990; Ertsen, 2016b).

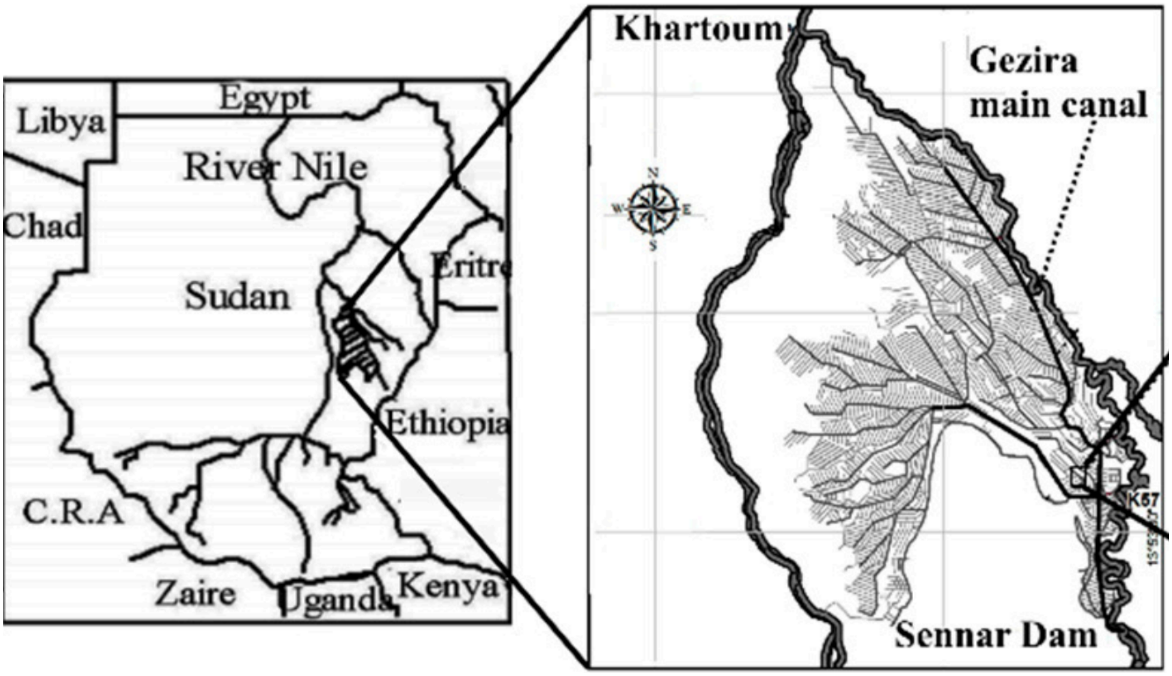


Figure 1.1: Map of the Gezira Scheme
(Theol et al., 2019).

Scientists have argued about why the Gezira Scheme, once thought of as the role model for planned development, had failed. Much of this debate surrounds the post-

World War II independence of the Sudanese state in 1956. Claims were made that infrastructure deterioration occurred as a result of decolonization and the transition of control from British colonists to the Sudanese (Eldaw, 2004). The argument is that a lack of trained personnel and proper maintenance caused sedimentation to worsen even through the turn of the 21st century (Plusquellec, 1990; Woldegebriel, 2011a). Today, sediment accumulation in the minor canals is considered the largest threat to the performance of the Gezira Scheme (Ali, 2020). Sedimentation in the canals diminishes their conveyance capacity, making it hard to maintain the desired water discharge (Ali, 2020). Due to a lack of systematic sediment measurements and unrealistic reporting on desilting efforts (Ahmed and Ismail, 2008; Ali, 2020), sedimentation in the Gezira Scheme still needs to be studied further.

This research focuses on disentangling the narrative around the cause of worsening sedimentation in the Gezira Scheme by assessing the effect of changing maintenance scenarios and environmental conditions on sediment accumulation in the minor canals. Claims that sedimentation became a problem only after independence due to inadequate maintenance imply that sedimentation was not an issue before the 1950s; this needs to be further investigated. Specifically, the shifting of maintenance responsibilities from centralized management to the tenants needs to be investigated to see its impact on sediment accumulation in the canals. By employing an agent-based model, the sedimentation trajectories under various environmental conditions and maintenance scenarios can be reconstructed despite a lack of consistent historical data. This gives further insight into how sedimentation in the Gezira Scheme developed over time and how this development impacts social relations between farmers and management.

1.1 Research Aim & Question

The aim of this research is to assess the effects of different environmental factors and maintenance strategies on sedimentation in the minor canals of the Gezira Scheme to illuminate the dominating driver of sediment accumulation over time. To this end, the proposed main research question is:

How do different environmental conditions and maintenance strategies impact sediment deposition in the minor canals of the Gezira Irrigation Scheme?

1.2 Research Sub-questions

To further understand sediment transport and accumulation in the Gezira Scheme, an agent-based modeling (ABM) approach was utilized in this research. ABM provides insight into how individual behavior of agents who follow certain rules within the same environment interact with each other to create global patterns of behavior (Cossart et al., 2018). The simulation can also integrate the role of the physical environment to predict the development of a system over time. Therefore, ABM can be applied to the Gezira Scheme to simulate potential historical trajectories of sediment deposition with different management strategies.

To answer the main research question, the following sub-questions were formulated to guide the methods of the research.

1. What theories underpinned the original design of the Gezira canals?
2. What impact did different environmental factors have on sedimentation in the Gezira canals?
3. What impact did different human factors, namely maintenance strategies, have on sedimentation in the Gezira canal system?
4. How can environmental and human factors be conceptualized into an ABM?
5. What scenarios can be tested by an ABM to pinpoint the cause of sedimentation in the Gezira canals?

The rest of this section details the methods used to address each sub-question.

Sub-question #1: What theories underpinned the original design of the Gezira canals?

To address sub-question #1, a literature review was conducted to identify the theories upon which the Gezira Scheme was designed. Understanding these theories gives insight into how the Gezira Scheme was originally constructed. Section 2.2 discusses how the Gezira canals were designed, reviewing Lacey's regime theory method.

Sub-question #2: What impact did different environmental factors have on sedimentation in the Gezira canals?

To address sub-question #2, a literature review was conducted to find the environmental factors that have impacted sedimentation in the Gezira Scheme. Environmental factors can make the operations and maintenance (O&M) of an irrigation canal system more complex. Understanding what contributes to this complexity illuminates the mechanisms that are relevant for studying and modeling sedimentation. Sections 2.3 and 2.4 discuss the environmental factors that impact the Gezira Scheme and its implications for management, respectively.

Sub-question #3: What impact did different human factors, namely maintenance strategies, have on sedimentation in the Gezira canal system?

To address sub-question #3, a literature review was conducted to identify the timeline and types of maintenance strategies used for the Gezira Scheme. The way in which an irrigation scheme is operated and maintained impacts the productivity of the canals. Sections 2.3 and 2.4 discuss the human factors that impact the Gezira Scheme and its implications for management, respectively.

Sub-question #4: How can environmental and human factors be conceptualized into an ABM?

To answer sub-question #4, a literature review was conducted to understand the complexity of modeling sedimentation and how existing literature has used ABMs to study sediment transport; Sections 2.5 and 2.6 discuss these topics, respectively. In addition, the outputs of sub-question #1 along with sediment transport principles informed the development of the Gezira Sedimentation Agent-based Model (GSAB Model). Then, the outputs of sub-questions #2 and #3, environmental and human factors, were incorporated into the GSAB Model. Chapter 3 details the model's design.

Sub-question #5: What scenarios can be tested by an ABM to pinpoint the cause of sedimentation in the Gezira canals?

To answer sub-question #5, scenarios were developed to investigate the impact of various maintenance strategies and environmental factors discovered through answering sub-questions #2, #3, and #4. One unstructured interview with a Sudanese expert currently working on the Gezira Scheme was conducted to verify the model assumptions. Based on the outputs of previous sub-questions, scenarios were developed as shown in Section 3.8.

In sum, the outputs of sub-questions #1, #2, #3, and #4 were used to build the GSAB Model. The GSAB Model simulates the mechanism of sediment deposition and maintenance in the minor canals of the Gezira Scheme. Then, scenarios that were created by answering sub-question #5 were simulated over 100 years. The net sediment deposition was monitored to see how much sediment accumulates in the minor canals for each scenario. The results of these scenario runs were analyzed to see how environmental and human factors influenced net sediment deposition in the canals.

1.3 Study Area

The Gezira Scheme is one of the largest irrigation systems in the world (Osman, 2015). It is located in Sudan in a semi-arid to arid region. 35% of the water from the Nile River flows to the Gezira Scheme; this is approximately six to seven million cubic meters (m^3) of water per year (Osman, 2015). More specifically, the Gezira canals stem from the Blue Nile River and are gravity-powered. Along with a high variation in water inflow from the Blue Nile River, there is also high fine sediment load (Plusquellec, 1990; Eldaw, 2004; Osman, 2015). In total, the two main canals – the Gezira Main Canal and Manaqil Main Canal – span 261 kilometers (km); the minor canals span 8,000 km (Ahmed, 2009; see Figure 1.1).

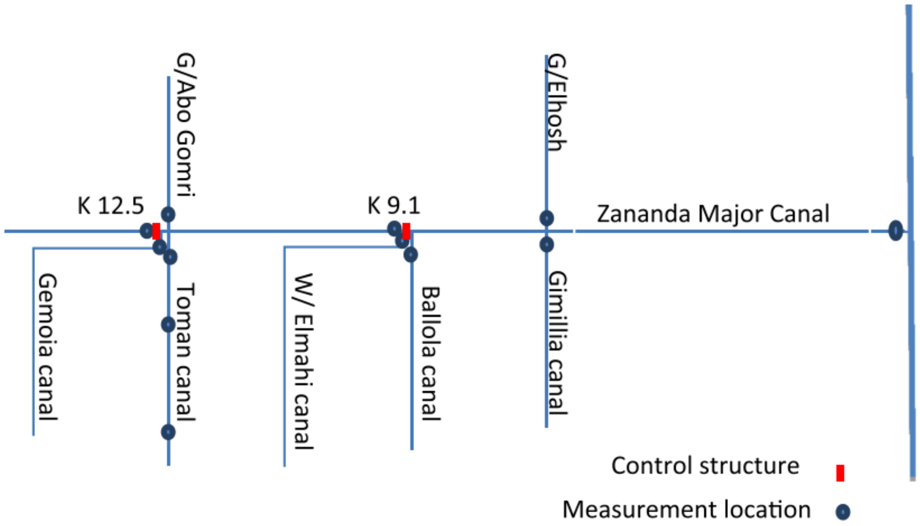


Figure 1.2: Diagram of the Zananda Major Canal and its minor canals (Osman, 2015).

The specific study area for this research is the Zananda Major Canal and its seven minor canal offtakes: G/Elhosh, Gimillia, Ballol, W/Elmahi, Gemoia, Toman, and G/Abu Gomri (Figure 1.2). The location of the Zananda Major Canal offtake from the Gezira Main canal is at 14°01'01.9"N 33°32'30.5"E (K57 in Figure 1.2).

1.4 Thesis Layout

Chapter 1 is the introduction to this research. Chapter 2 contains a literature review of the Gezira Scheme's characteristics, influencing factors on sedimentation, and modeling methods used to study sedimentation. Chapter 3 details the methods employed for this research, namely for the design and scenario implementation of the Gezira Sedimentation Agent-based Model (GSAB Model). Chapter 4 presents the results of the sensitivity analysis and sediment deposition simulations without maintenance. Chapter 5 shows the results of the model's scenarios with different environmental conditions and maintenance strategies. Chapter 6 offers a discussion and conclusion, and Chapter 7 ends this research with a reflection.

Chapter 2

Literature Review

This chapter presents a literature review of the characteristics of the Gezira Scheme (Section 2.1), design of irrigation systems (Section 2.2), environmental and human factors impacting sedimentation in Gezira (Section 2.3), and their implications for the management of the Gezira Scheme (Section 2.4). The initial design of the Gezira Scheme and management strategies employed by various stakeholders impact the functioning of the system and add to the complexity of managing it. While models help to investigate sediment transport and accumulation dynamics, their application to modeling irrigation systems produces complexities, especially when the role of other environmental and human factors are included (see Section 2.5). Agent-based modeling (ABM) is one method that can be used to study isolated scenarios of environmental contributors and maintenance strategies and their impact on sedimentation (see Section 2.6).

2.1 Gezira Scheme Characteristics

This section discusses the Gezira Scheme characteristics, detailing its climate, system design, hydrology and sedimentation characteristics, and operations and maintenance.

2.1.1 Climate

The climate at the Gezira Scheme is characterized as arid and semi-arid, with a low average annual precipitation and high evaporation rates (Osman, 2015). Most of the rainfall occurs between July and September, peaking in August (Mamad, 2010; Osman, 2015). There is a high fluctuation of rainfall intensity and distribution from year to year (Plusquellec, 1990). Plusquellec (1990) states, “There are three distinct seasons: a short rainy season from July to September, during which the temperature is moderate and the humidity high; a cool dry winter season from November to February; and a hot summer from April to June. March and October are transitional months.”

2.1.2 Hydrology & Sedimentation Characteristics

In the early years of operation, the Gezira Scheme received anywhere between five to seven million cubic meters of sediment annually (Plusquellec, 1990). Ali et al. (2021) state that the Gezira Scheme received around six million cubic meters annually, most of which was fine sediment containing silt and clay with less than 63 microns in diameter (Gismalla, 2009). This means that the sedimentation in the Gezira Scheme is characterized by wash load with the sediment transported in suspension. The silt distribution on the main, major, minor, and field canals are 4%, 23%, 35%, and 38%, respectively (Ali et al., 2021). The maximum sediment concentration occurs in July, with 70% to 80% of the sediment entering the system between mid-July and mid-August (Plusquellec, 1990; Gismalla, 2009). Osman (2015) notes that sediment accumulation has caused the following issues in the Gezira Scheme:

- Reduced canal conveyance,
- Reduced irrigation capacity which decreased crop production,
- Reduced water supply and higher inequality of water distribution,
- Increased aquatic weed growth, and
- Reduced water level which caused the canal sections to widen and the canal bed to rise.

Sediment Transport

In the Gezira Scheme, the sediment are less than 63 microns in diameter; this means that they are considered cohesive sediment transport (Lawrence and Atkinson, 1998; Gismalla, 2009; Osman, 2015). Cohesive sediment are transported via flocs or aggregates that are formed depending on the sediment concentration, turbulence, and physical, biological, and chemical properties of the sediment. The effective density of flocs in the Gezira Scheme is low because it contains both water and sediment (Osman, 2015). The sediment are carried in large amounts by the water flow.

The D_{95} for main, major, and minor canals is 25, 24, and 21 microns, respectively (Osman, 2015). This indicates that 95% of the sediment in main canal have less than 25 microns in diameter. According to Partheniades (2009), cohesive sediment are less than 50 microns in diameter. High concentrations of fine, cohesive sediment might turn water flow into mud flow. The sediment transport is influenced by 1) Sediment characteristics such as size, settling velocity, shape, dispersion, cohesion and 2) Capacity of water channels to transport sediment (canal dimensions and hydraulic properties like slope, roughness, hydraulic radius, velocity distribution, discharge) (Simons and Şentürk, 1992). Within irrigation channels, other factors like control structures, operational rules, and water delivery schedules also impact sediment transport (Osman, 2015).

Deposition

Deposition of cohesive sediment is influenced by bed shear stress, turbulence, settling velocity, water depth, sediment type, suspended concentration, and ionic characteristics of suspended fluid (Partheniades, 2009). Deposition occurs when the critical shear stress is greater than the bottom shear stress (Osman, 2015). According to the study by Osman (2015), sediment concentration and settling velocity are the main influencing factors for sediment deposition.

Erosion (Resuspension)

Resuspension of sediment occurs when the bed shear stress exceeds the critical shear stress (Osman, 2015). Osman (2015) gives a range of 0.04 to 0.62 Newtons per square meter (N/m^2) for the critical shear stress of erosion, while Winterwerp and Van Kesteren (2004) gave a range of 0.1 to 5 N/m^2. The higher the shear stress rate, the muddier the water. Lawrence and Atkinson (1998) indicate that bed shear is limited in small channels where there is low flow and depth; there is little resuspension in these smaller channels.

2.1.3 Operations & Maintenance

The Gezira Scheme was operated on an indent system by the SGB (Ministry of Irrigation and Hydro-Power, Sudan, 1934). The indent is the required fixed water discharge that should be supplied; this design maintains the irrigation canals at a fixed water level and requires that ongoing O&M maintains the water level within a certain range (Ministry of Irrigation and Hydro-Power, Sudan, 1934). For the Zananda Major Canal, the required discharge is 30 m^3 per feddans per day (Osman, 2015; Plusquellec, 1990). Along with the indent system, the Gezira Scheme was designed with the intention to have the minor canals irrigate fields only for 12 hours during the day and store water during the night; however, this night storage system is not used today (Ali et al., 2021). The Gezira Scheme was operated on a policy to start the impounding of water as late as possible in the year, typically around early September; this minimizes the amount of trapped sediment when the Roseires reservoir was filling which maintains a high trap efficiency (Gismalla, 2009).

2.2 Design of Irrigation Systems

According to Mendez (1998), an irrigation system is a network of hydraulic infrastructure that functions to transport and distribute water to farms. Typically, irrigation systems have a management organization tasked with operating and maintaining the hydraulic infrastructure. There could be two management levels: 1) the main level which is the central irrigation authority, and 2) the unit level which is managed either by farmers or by a water user's organization. The design of the irrigation system must be sufficient to meet the water demand of water users according to its water delivery method; moreover, it should be designed to ensure the least amount of sedimentation and scouring in the canals (Mendez, 1998).

There are four potential methods of irrigation canal design: 1) Tractive Force Method, 2) Maximum Permissible Velocity, 3) Rational Method, and 4) Regime theory (Mendez, 1998). The tractive force method uses two known variables to determine two unknown variables for the design of stable channels. The variables to determine are water depth, bed slope, bed width, and grain size (US Army Corp of Engineers, 2022). The tractive force "can be defined as the force that is resisted by friction force and, while in equilibrium, is equal and opposite in magnitude and direction" (US Army Corp of Engineers, 2022). The tractive force is also known as shear stress. This method aims pinpoint when the canal becomes unstable, when the tractive force exceeds the critical shear stress.

Permissible velocity methods are used to design canals based on their erodibility (Depeweg and Méndez, 2007). The minimum permissible velocity is the velocity at which there is no sedimentation or aquatic weed growth (Depeweg and Méndez, 2007). The maximum permissible velocity is the maximum water velocity that does not cause erosion – the resuspension and transport of sediment that could potentially be deposited downstream at a later time (Ali et al., 2021). Ideally, the canal cross-section should be determined so that it generates a water velocity that is equal to or below the maximum permissible velocity that could be resisted by the material of the canal (Ali et al., 2021). In reality, it is challenging to pinpoint the maximum permissible velocity, as it changes depending on the context (Ali et al., 2021). Therefore, it is mainly determined by experience and sound judgment (Depeweg and Méndez, 2007). Yet, Table 2.1 gives an indication of the maximum permissible velocities of various sediment types.

Material	Manning N	Clear water V (m/s)	 τ (N/m^2)	Silt-loaded water V (m/s)	 τ (N/m^2)
Fine sand, colloidal	0.02	0.46	1.30	0.76	3.61
Sandy loam, non-colloidal	0.02	0.53	1.78	0.76	3.61
Silt loam, non-colloidal	0.02	0.61	2.31	0.91	5.29
Alluvial silts, non-colloidal	0.02	0.61	2.31	1.07	7.22
Ordinary firm load	0.02	0.76	3.61	1.07	7.22
Volcanic ash	0.02	0.76	3.61	1.07	7.22
Stiff clay, very colloidal	0.025	1.14	12.51	1.52	22.13
Alluvial silts, colloidal	0.025	1.14	12.51	1.52	22.13

Table 2.1: Maximum permissible velocity of various sediment where V refers to the velocity and τ refers to the tractive force (adapted from Depeweg and Méndez, 2007).

In the rational method, four canal dimensions are determined: 1. bed slope (S_0), 2. bed width (b), 3. water depth (h), and side slope (m). First, the side slope is determined based on soil characteristics and the estimated water depth (Depeweg and Méndez, 2007). Then, friction coefficients like the Chezy, Manning, or Strickler coefficients and their equations can be used to determine the sediment transport efficiency. This method is best suited for the design of canals with low flows and low variations in flow and sediment loads (Depeweg and Méndez, 2007).

Regime theory is based on a design where the canal dimensions and geometry do not change over typical water years (Ali et al., 2021). The British used their experience in India to apply the regime theory method in the design the Gezira canals which were intended to be non-scouring and non-silting (Plusquellec, 1990; Gismalla, 2009; Osman, 2015; Ertsen, 2016a). A set of empirical regime theory equations are used to determine the design of the canals. The most used set of equations were developed by Gerald Lacey in 1930 (Lacey, 1930). The regime theory equations are based on empirical data from canals and rivers that have achieved dynamic stability. They specify the cross-sectional area and slope of canals from a constant incoming discharge and bed material size (Osman, 2015). By assuming that the overall canal dimensions do not change in one water year, regime theory assumes that the sediment input into the canals matches the average sediment transport capacity (Osman, 2015).

While the regime theory method was praised for being based on a large set of empirical data from large and small canals, making extrapolation unnecessary (Barr et al., 1970), it has several drawbacks. First, the dataset on which the Lacey regime theory equations were derived was incomplete (Stevens and Nordin Jr, 1987). The incomplete data caused Lacey to relate his silt factor to channel roughness, when it should have been related to sediment concentration (Stevens and Nordin Jr, 1987).

Therefore, the silt factor limits the characterization of the silt and disregards the impact of sediment concentration on the canal system. In addition, relating the silt factor to channel roughness conflated two types of silt factors, creating redundancy in the development of two separate sediment transport equations (Stevens and Nordin Jr, 1987). These errors limit the capacity of the canal to accommodate larger sediment loads or water flows than those of its original design (Stevens and Nordin Jr, 1987). Canals that are designed based on Lacey's regime theory, such as the Gezira canals, are expected to be managed under strict operational guidelines, leaving little room for the canals to remain resilient under different environmental conditions. This poses risks for the productivity of the canal, as there is little margin for error. In the event of a higher sediment load or water flow, the canals would be overrun with sediment.

2.2.1 Gezira Irrigation System Design

The Gezira Scheme was designed in the 1920s based on empirical experimentation; the scheme's main objective was to enable the production of cotton, so the system was designed to match the crop rotation schedule and size of fields (Plusquellec, 1990). The scheme is irrigated by two main canals: the Gezira Main Canal and the Manaqil Main Canal, with a design capacity of 168 and 186 cubic meters per second (m^3/s), respectively (Osman, 2015). The scheme is fed by gravity flow from the Sennar Dam on the Blue Nile River (Plusquellec, 1990). The Gezira Main Canal supplies water to the Zananda Major Canal, which then supplies water to its minor canals. The distribution of water flow between the major and minor canals is controlled by weirs (Johnstone, 1929; Osman, 2015). The minor canals were designed according to Lacey's regime theory and an estimated Manning's roughness coefficient; the minor canals had a night storage system where they acted as water reservoirs that store water during the night while the water continuously flowed from the Zananda Major Canal (Plusquellec, 1990; Osman, 2015). The minor canals deliver water to the fields through field outlet pipes. The fields are divided into parallel groups called Nimras. A schematized map of the Gezira Scheme is shown in Figure 2.1.

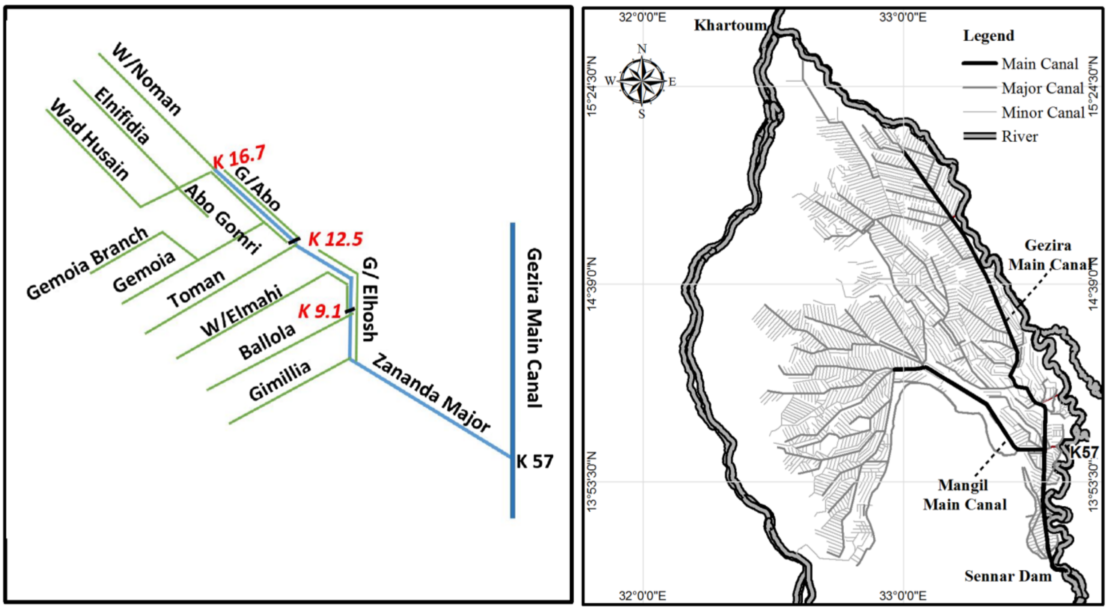


Figure 2.1: Schematic and map of the Gezira Scheme (Osman et al., 2016).

Table 2.2 summarizes the characteristics of the Gezira Irrigation Scheme's canal network, and Table 2.3 details the characteristics of the Zananda Major Canal in particular. The Zananda Major Canal has two cross regulators, namely movable weirs, at K9.1 and K12.5 with a crest of two meters and 1.3 meters, respectively (Ali, 2020; see Figure 2.1).

Canal Type	Number	Total Capacity (m^3/s)	Total Length (km)	Average Width (m)
Main	2	354 (168 for Gezira, 186 for Manaqil)	261	50
Branches	11	25-120	651	30
Major	107	1.2-15	1652	20
Minors	1498	0.5-1.5	8119	6

Table 2.2: Characteristics of the Gezira Scheme canal network (adapted from Osman, 2015 and Plusquellec, 1990).

Zananda Major Canal Characteristics	
Position of offtake along Gezira Main Canal	57 km
Area of command	8,520 ha
Effective length	17 km
Number of reaches	3
Design discharge	3.52 m^3/s
Full capacity of the canal	5.5 m^3/s
Number of supplied minor canals	9

Table 2.3: Characteristics of the Zananda Major Canal (adapted from Osman et al., 2017 and Ali, 2020).

The canals in the Gezira Scheme were designed as regime conveyance channels where the aim was to maintain a constant water discharge rate (Osman, 2015). In his study of 39 canal reaches in Gezira, Matthews (1952) found that the Lacey regime equations are applicable for the Gezira Scheme and that its canal dimensions are determined based on known stable canals. He concluded that the Lacey silt factor (f) equals 0.63 for the Gezira canal design. Table 2.4 shows the different values of Lacey's silt factor for different sediment types.

Type of material	Size of grains (mm)	Silt factor (f)
Silt		
Very fine	0.052	0.4
Fine	0.081	0.5
Medium	0.158	0.7
Standard	0.323	1.0
Sand		
Medium	0.505	1.25
Coarse	0.725	1.50
Gravel		
Medium	7.28	4.75
Heavy	26.1	9.0
Boulders		
Small	50.1	12.0
Medium	72.5	15.0
Large	183.8	24.0

Table 2.4: Lacey's silt factor for different sediment types (adapted from Shrestha et al., 2012).

The Lacey equations are shown in Equations, 2.1, 2.2, and 2.3.

$$P = K_p \cdot Q^{(\frac{1}{2})} \tag{2.1}$$

$$A = K_a \cdot Q^{(\frac{5}{6})} \tag{2.2}$$

$$S_0 = K_s \cdot Q^{(-\frac{1}{6})} \tag{2.3}$$

where:
R = hydraulic radius [m]
P = wetted perimeter [m]
Q = discharge [$\text{m}^3 \cdot \text{s}^{-1}$], taken to be the average maximum authorized water flow in the design (Osman, 2015)
A = cross-sectional area [m^2]
S_0 = bed slope [$\text{cm} \cdot \text{km}^{-1}$]
K_p, K_a, K_s = constants [-]

Gismalla (2009) summarizes the empirical constants that are applicable for the Lacey equations of the Gezira Scheme (see Table 2.5). These constants are empirically determined based on the type of sediment of the canal bed and the magnitude of sediment transport (Osman, 2015).

Formula	Constant	Main Canals	Major Canals	All Canals
$V = \frac{1}{n}R^{\frac{2}{3}}S^{\frac{1}{2}}$	n	0.021	0.017	0.018
$P = K_pQ^{\frac{1}{2}}$	K_p	4.55	5.51	5.26
$A = K_aQ^{\frac{5}{6}}$	K_a	2.75	2.60	264
$S = K_sQ^{-\frac{1}{6}}$	K_s	14.57	13.90	14.5

Table 2.5: Lacey equations with empirical constants for the Gezira Scheme (adapted from Gismalla, 2009). In this table, V refers to the water velocity [m/s], and n refers to the Manning's roughness coefficient [$\text{s/m}^{(1/3)}$].

2.3 Environmental and Human Factors Impacting Sedimentation in the Gezira Scheme

2.3.1 Operations and Management Stakeholders of Gezira's Canals

During colonial times, the maintenance of the irrigation system was carried out by the Sudan Plantation Syndicate (SPS), a British firm (Woldegebriel, 2011a). After independence in the 1950s, maintenance responsibilities were divided between two organizations: Sudan's Ministry of Irrigation and Water Resources (MOIWR) and the Sudan Gezira Board (SGB) (Eldaw, 2004; Plusquellec, 1990). The MOIWR became responsible for the maintenance of the irrigation network, while the SGB managed the maintenance of the irrigation structures of the minor canal and the railways used to transport agricultural products like cotton (Woldegebriel, 2011a). These two organizations shared one budget and obtained their revenue by charging tenants for water use. In 1974, the construction and mechanical divisions of the MOIWR split into two corporations: Earthmoving Corporation (EMC) and Irrigation Water Corporation (IWC) (Woldegebriel, 2011a). The EMC, IWC, and SGB continued in their management roles until 1995, when it started to become difficult to collect water charges from tenants. As a result, the charge collection responsibility was given to the IWC; however, they did not have the capacity to collect charges so the SGB became responsible for collecting charges and maintaining the minor canals at the field level (Eldaw, 2004). Without adequate water charge collection, the recovery of costs was low which led to insufficient desilting and deterioration of the canal function. In 2005, the Gezira Scheme Act came into effect which handed over all O&M responsibilities to the Water User Association (WUA), created to act as a liaison between farmers, the SGB, and the MOIWR (Woldegebriel, 2011a). Maintenance of minor canals was conducted by tenants until 2020, when it was transferred back to the Sudanese government.

2.3.2 Sedimentation Issues

Records from the MOIWR show that in the month of August from years 1933 to 1938, the mean sediment concentration entering the main canal was 700 ppm; by 1988, they measured an increase in mean sediment load to 3,800 ppm (Osman, 2015). From the late 1980s to 2003, the MOIWR recorded an increase to 7,900 ppm (Osman, 2015). In addition, there has been scarce and conflicting data on sediment accumulation rates with data collection done at various locations within the Gezira Scheme. For example, Elhassan and Ahmed (2008) state that the annual amount of sediment deposition in irrigation canals is 16 million m^3, but El Monshid et al. (1997) cite 19 million m^3. Systematic measurements of silt entering the system started in 1988 by the Hydraulic Research Station (HRS) and Hydraulic Research Ltd. UK, but ended in 1989 (Woldegebriel, 2011a). Records from the MOIWR indicate that 41.0 million m^3 of sediment were removed from the Gezira canals in 1999; if this is true, that means that the canals were over-dredged and the bed profile widened (Ahmed and Ismail, 2008). Additionally, reports from the MOIWR in the early 2000s document unrealistic desilting numbers (Ahmed and Ismail, 2008). More recently, several empirical studies have been conducted using field data at a short-term time scale, most notably by Plusquellec (1990), World Bank and Government of

Sudan (2000), Osman (2015), and Osman et al. (2016). Table 2.6 shows a summary of available data on sediment characteristics of the Gezira Scheme.

Source	Time Frame	Location	Value
Mean Sediment Concentration			
MOIWR	1933-1938	Gezira Main Canal	700 ppm
MOIWR	1988	Gezira Main Canal	3,800 ppm
MOIWR	1980s-2003	Gezira Main Canal	7,900 ppm
Mean Amount of Sediment Entering the System			
Gismalla, 2009	1995-2008	Gezira Main Canal	8.5 M tonnes/yr
Mean Sediment Load Entering the System			
Gismalla, 2009	1995-2008	Gezira Main Canal	0.56 M tonnes/yr
Mean Sediment Deposition Rate			
El Monshid et al., 1997	1997 Study	Whole System	19 Mm^3/yr
Elhassan and Ahmed, 2008	2008 Study	Whole System	16 Mm^3/yr
Mean Sediment Removal Rate			
World Bank and Government of Sudan, 2000	1930s	Whole System	5 to 7 Mm^3/yr
Plusquellec, 1990	1973-1977	Whole System	4.2 Mm^3/yr
Plusquellec, 1990	1983	Whole System	6.2 Mm^3/yr
Plusquellec, 1990	1990	Whole System	11 Mm^3/yr
Osman, 2015	1999	Whole System	41 Mm^3 in 1999

Table 2.6: Available data on sediment characteristics of the Gezira Scheme.

2.4 Implications of Canal Design and Environmental & Human Factors for Managing the Gezira Scheme

Successful management of large irrigation systems like the Gezira Scheme is a complex endeavor as multiple factors, such as the original design and management stakeholders, play a role in maintaining the function of the canal system. Because of the multitude of potential contributing factors and a lack of systematic study on the root cause of the canal system's deterioration, many claims in literature have been made in an attempt to explain why sedimentation has worsened over the last century (see Table 2.7). Specifically, the pivotal point of worsening sedimentation is thought to be decolonization, when the Sudanese gained independence in the 1950s and control of the Gezira Scheme transitioned from the British to the Sudanese (Eldaw, 2004). Scientists argue that a lack of trained personnel and adequate maintenance further exacerbated sedimentation in the canals (Plusquellec, 1990; Woldegebriel, 2011a). According to a Sudanese expert currently working on the Gezira Scheme, the sediment depth in the minor canals could be as high as two meters, even when maintenance was centrally managed. Historically, centralized maintenance was not conducted systematically. There was no defined order in which minor canals were desilted, and oftentimes, excavators would also dig part of the bed. This changed the bed profile until the canals no longer performed like the non-scouring Lacey regime theory canals they were designed to be.

#	Cause	Reference
1	Poor management and lack of financial investment, exacerbated by slump in exports and price of cotton	Woldegebriel, 2011b; Elhassan and Ahmed, 2008; Plusquellec, 1990; Eldaw, 2004
2	Increased crop production, diversification of crops, and change of planting season starting in the 1960s that increased water demand	Woldegebriel, 2011b
3	The Manaqil Extension (built in the 1960s) that increased water volume (2 to 7.1 billion m^3) into the Gezira system and therefore, more sediment	Plusquellec, 1990; Eldaw, 2004
4	Erosion from Ethiopian Highlands due to deforestation, overgrazing, overfarming, drought (dry-wet season alternating), and population growth in the 2000s	Ahmed and Ismail, 2008; Balthazar et al., 2013; Eldaw, 2004; Plusquellec, 1990; Gismalla, 2018
5	Management changes and improper management along with changing operational rules	Ahmed and Ismail, 2008; Setegn et al., 2009; Plusquellec, 1990

Table 2.7: Causes of sedimentation in the Gezira Scheme.

Further study is required to investigate the validity of these claims and to find which is the dominating cause of the sedimentation issue in Gezira. For example, the original canal design, shifting management responsibilities, environmental factors, or a combination of these three factors could have significantly contributed to sediment accumulation over time. Yet, sporadic and incomplete records on sedimentation in the Gezira Scheme make it hard to pinpoint its root cause. This has implications for changing social relations and power dynamics between management and tenants. Upstream processes impact downstream water distribution, which leads to rising inequality and a reduction in a return on investment (Ahmed, 2009). Blame is placed on the poor for overusing land resources and causing erosion downstream (Ahmed and Ismail, 2008). In addition, claims persist that before independence, the system was operating as designed so there were few sedimentation problems; the belief is that sedimentation worsened only after independence due to a slump in export prices and poor tenant-run management including a lack of equipment and trained personnel (Plusquellec, 1990; Woldegebriel, 2011b). In the absence of data, agent-based modeling can be used to investigate the complexity of the design and management of the Gezira Scheme and its impact on sedimentation.

Figure 2.2 summarizes the timeline of changing management and environment conditions that have impacted sedimentation in the Gezira Scheme over the last century, as discussed in Section 2.3.1 and 2.4.

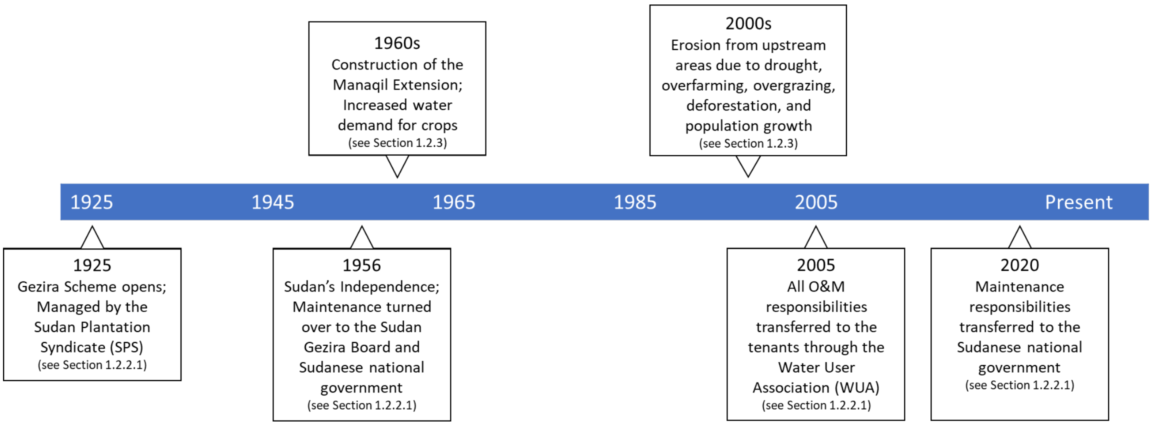


Figure 2.2: Timeline of key management stakeholders and environmental factors impacting sedimentation in the Gezira Scheme.

2.5 Complexity of Modeling Sedimentation and Human Factors

The close relationship between human social dynamics and physical environmental factors that impact sedimentation generates complexity in studying the causes of sedimentation in isolation. Furthermore, sediment transport predictions tend to have substantially lower accuracy than water flow predictions (Mendez, 1998). Sediment transport has mainly been studied in natural channels like rivers rather than irrigation channels. Though there are some similarities between rivers and irrigation channels, not all equations and theories applied to the study of rivers can be translated to irrigation channels, as shown in Table 2.8. For example, irrigation channels have a wider variety of flow control structures and water flow paths; its design and cross section need to be designed in such a way that a particular water level or discharge is maintained (Mendez, 1998). In addition, most existing methods used to design irrigation channels are based on water flow and sediment transport equations in an equilibrium condition. However, most irrigation channels operate under non-equilibrium conditions (Depeweg and Méndez, 2002). Depeweg and Méndez

(2002) encourage the use of different water flow and sediment transport scenarios to analyze irrigation channels to consider operational scenarios more generally.

	Water flow and sediment transport	
	Rivers	Irrigation canals
Water flow		
Water profiles	Nearly steady flow	Gradually varied flow
Froude number	Fr <1	Fr <0.4
Discharge	Not controlled	Controlled by operation rules
Flow control	Almost no control structures	Several control structures for water level and discharge
Width (B)/depth (h)	B/h >15 (wide canals)	B/h <7-8
Velocity distribution	Constant velocity in width direction	Velocity distribution strongly affected by side wall
Alignment	Hardly straight, meandered & braided	Straight
Lining	Alluvial river bed	Man-made canals: lining/no lining
Sediment transport		
Sediment size	Wide range of sediment size	Fine sediment
Size distribution	Graded sediment	Nearly uniform distribution
Sediment material	Mother material	External sources
Sediment transportation	Suspended and bed loads	Mainly suspended loads
Bed forms	Mostly dunes	Mostly ripples and mega-ripples
Roughness	Skin and form friction	Form friction
Concentration	Wide range	Controlled at headwork

Table 2.8: Water & sediment transport properties in rivers versus irrigation canals (adapted from Depeweg and Méndez, 2002).

While there are a plethora of models that study the physical processes of sediment deposition and transport, there remains a need to model the historical trajectory of human and environmental factors that impact sedimentation. One method that enables the researcher to study interdependent processes and isolate them in different scenarios is ABM. An ABM allows for the exploration of the interaction between sedimentation and the canal system design while simulating various environmental and management scenarios. By modeling sediment flow through the canals and layering scenarios of varying environmental conditions and maintenance strategies, it is possible to investigate the root cause of sedimentation.

2.6 Agent-based Modeling of Sediment Transport

Agent-based modeling (ABM) provides a way to analyze the different possible trajectories of history to test current theories about the physical and social dynamics that shaped the system over time (Romanowska et al., 2021). It allows the researcher to change assumptions on agent behavior and interactions that lead to global system behavior so that it can be compared with available data. The ABM environment allows for the simulation of "biophysical, economic, and social processes at different spatial and temporal scales" (Carlin et al., 2007). Various physical processes could produce the same sedimentation outcome; ABM allows the researcher to explore the interactions between non-human agents such as the interaction between sediment and hydrological flows to investigate its impact with different scenarios (Kabora et al., 2020). Moreover, in the absence of data, ABM can simulate potential outcomes by using logic and basic physical principles to determine the movement of the sediment.

Scientists and historians have used archaeological records to try to piece together the social hierarchies and environmental factors that shaped societies to what we know of them today. However, challenges rise when working with datasets from the past. As mentioned by Gould (1990) in this study of fossil beds, individual agency of human and non-human agents and their interactions lead history down particular trajectories that lead to the present day. According to Romanowska et al. (2021), simulation modeling provides a way to test theories against available data to help researchers reconstruct the past and analyze if theories about them are true. Understanding how simulation modeling has been used in existing literature to understand the dynamics of past societies helps form the methods that could be used to analyze the sedimentation issue in the Gezira Scheme.

Kabora et al. (2020) use ABM to simulate sediment accumulation rates in agricultural Tanzania between the 15^{th} and 18^{th} century. They disprove previous explanations of the causes of sediment deposition, showing instead that the field development of agricultural fields could occur over one-to-two-month periods with lower water flows than previously theorized. Their study shows that it is possible to better understand modern-day irrigation systems with little data by modeling scenarios over large timescales to assess sediment deposition and transport. Cossart et al. (2018) use agent-based modeling to 1) understand the impact of landscape on sediment connectivity (the transport of sediment from a source to a sink through geomorphic landscapes), 2) understand the impact of different man-made structures on sediment transport, and 3) infer the sources of sedimentation in a catchment in Western France. They conclude that ABM can be applied to conceptual frameworks such as sediment connectivity to investigate the complexity of geomorphic landscapes. Majumdar et al. (2018) conclude that ABM can be used to understand rainfall runoff and soil erosion in a watershed in India, yielding results comparable to traditional hydrological models. Giri et al. (2019) use ABM to simulate three scenarios of climate change and land use changes, concluding that land use changes towards suburban development compensated for the negative impacts of climate change by reducing sediment transport in a watershed in New Jersey, USA. Davies et al. (2016) use ABM to examine sediment transport in an Australian fluvial landscape and evaluate the causes of geomorphic features seen today. With ABM, they reconstruct several processes that could contribute to the geomorphic pattern observed today, calling into question current hypotheses on the causes of sedimentation (i.e., demographic changes and human mobility). Therefore, ABM helped to disentangle the current interpretations of archaeological records and functioned as a basis for future studies.

Chapter 3

Methodology: Gezira Sedimentation Agent-based (GSAB) Model Design and Scenario Implementation

This chapter details the design of the Gezira Sedimentation Agent-based Model (GSAB Model) which models sediment transport from the Zananda Major Canal to its minor canals under various flow conditions and management scenarios. In addition, sediment deposition and maintenance of the minor canals are modeled. The GSAB Model is constructed in the Netlogo platform version 6.2.2 (Willensky, 2021) and is organized based on Müller et al. (2013)'s ODD+D protocol. The problem and purpose of the model are discussed along with assumptions used to create the model. In addition, key parameters and data sources used for the parameters are provided. This chapter also includes a sensitivity analysis and a description of scenarios that are simulated in this research.

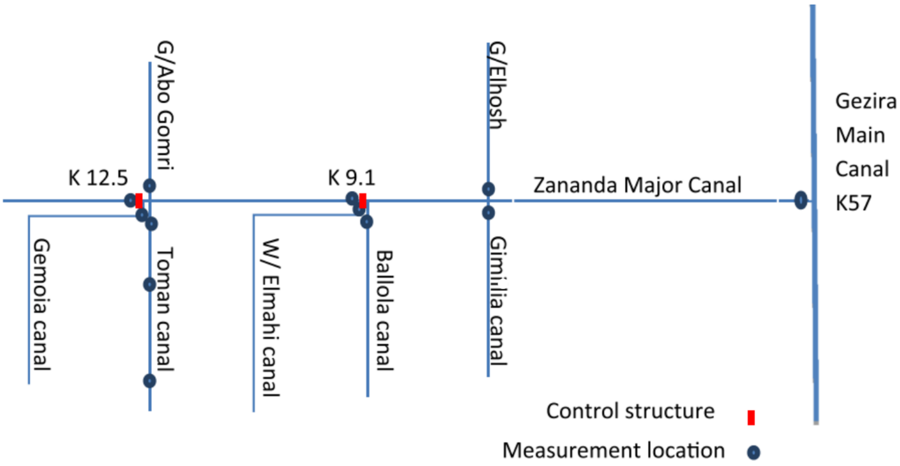
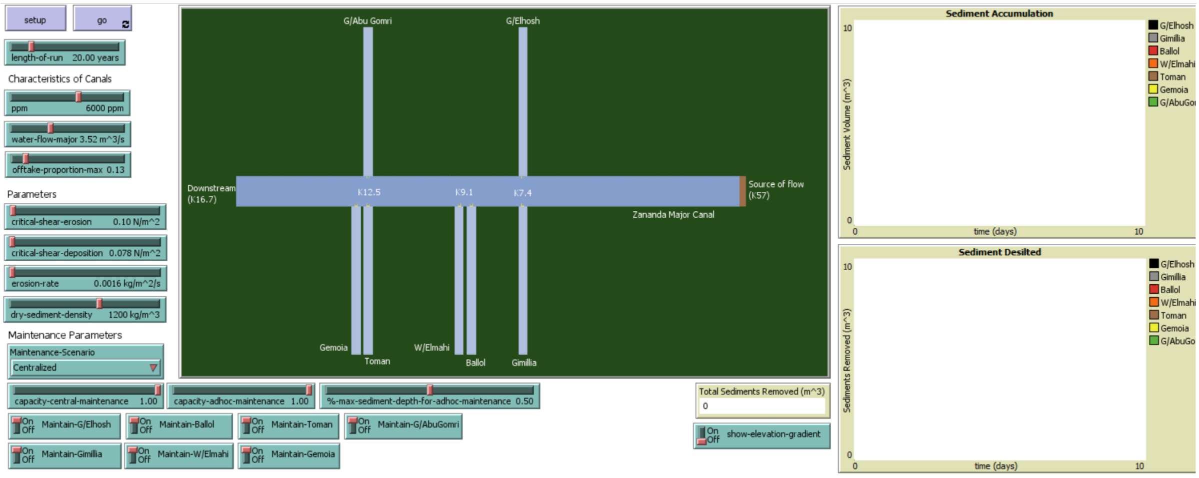


Figure 1.2: Diagram of the Zananda Major Canal and its minor canals (I. S. E. Osman, 2015).

The GSAB Model of the Gezira Scheme is based on the schema shown in Figure 1.2. The model focuses on the Zananda Major Canal and its minor canals since, according to Ali et al. (2021), 35% of sedimentation occurs in the minor canals compared to only 23% in Zananda Major Canal and 4% in main canals. To predict sediment transport and deposition in the minor canals, mathematical equations based on hydraulic processes are used (Depeweg and Méndez, 2002). This is adequate for the study of sediment transport because sediment are transported by water (Cunge, 1980). In sediment transport and water flow mathematical formulations, one-dimensional flow is usually assumed and modeled under quasi-steady state conditions where the water flow remains constant (Depeweg and Méndez, 2002).

Figure 3.1 shows the Netlogo interface of the Gezira canals. The canal dimensions were scaled from actual canal dimensions found in literature, with each canal patch containing elevation data. The sediment agents start at the source of the flow (K57) and travel downstream towards K16.7, mimicking gravity flow. At K16.7, the water drainage is modeled by removing sediment agents that have reached the end of the Zananda Major Canal. More detail on the model design will be given in the subsequent sections.



length-of-run 20.00 years
Characteristics of Canals
ppm 6000 ppm
water-flow-major 3.52 m^3/s
offtake-proportion-max 0.13
Parameters
critical-shear-erosion 0.10 N/m^2
critical-shear-deposition 0.078 N/m^2
erosion-rate 0.0016 kg/m^2/s
dry-sediment-density 1200 kg/m^3
Maintenance Parameters
Maintenance-Scenario: Centralized
capacity-central-maintenance 1.00
capacity-adhoc-maintenance 1.00
%-max-sediment-depth-for-adhoc-maintenance 0.50
Total Sediments Removed (m^3): 0

Figure 3.1: Netlogo model interface.

Developed by Willensky (2021), Netlogo is an openly available software package for ABM. Netlogo was selected as it has a number of strengths, the main one being that the code is simple and easy to use for non-coders (Van Dam et al., 2012). Moreover, it has a graphical user interface that allows the user to visualize the model and to update model parameters easily. This allows the modeler to change the model controls easily without having to devote extra time to recode the model.

3.1 GSAB Model Purpose and Patterns

The purpose of the model is to depict sediment transport and accumulation in the minor canals to see how they are affected by various environmental factors and maintenance scenarios across time and space. To determine whether the model is realistic enough for this purpose, the following macro-level patterns are expected:

- Sediment accumulation over time will slow down because as the minor canals are filled with sediment, less water can flow through the canals, bringing in less sediment. In other words, the sediment accumulation rate is not expected to remain constant over time. Rather, the sediment accumulation rate should decrease as the minor canals fill up.
- Sediment accumulation occurs within years even with regular centralized maintenance. Even during colonial times when maintenance was conducted in a centralized manner, the dredged sediment had to be dumped in the main canal because there was no other available space to dump such a large amount of sediment (Gismalla, 2009).

In addition, the sediment accumulation rate in the Zananda Major Canal is approximately 354 m^3 in the first three days of operation at design conditions; this is calculated from the model results of the Osman (2015) study. This is equivalent to a sediment depth of 4.2 millimeters (mm) in the Zananda Major Canal.

3.2 GSAB Model Entities, State Variables, and Time Scale

This section details the ontology of the model – the concepts and items that are represented within the model.

Entities and State Variables

The entities in the model are objects and agents that have distinct characteristics and behavior. The model has two entities: sediment agents (turtles) and the canal network (patches). The model is spatially and temporally explicit, as it shows sediment transport and variations in sediment accumulation across space and time.

State variables of the entities are its attributes; they describe the current state of an entity, distinguish it from other entities, and show how an entity changes over time. The sediment agents have eight state variables: its position (x- and y-coordinates), the cross-sectional area (A), bed slope (S_0), water discharge (Q), sediment discharge (Q_s), sediment volume (V_s), deposition flux (D), and erosion flux (E). The cross-sectional area and bed slope are state variables of the sediment agents because this allows for the sediment agents to calculate the shear stress (τ_b) at a particular location based on the Lacey equations. Additionally, as the model runs, the sediment budget that the sediment agents calculate will vary from patch to patch. Since the patches of the model interface are fixed, the variation of the bed slope and cross sectional area and their effects on the sediment budget are calculated by the sediment agents. They are calibrated by a scale factor to fit available empirical data by Osman (2015).

At each time step, sediment agents calculate the value of these state variables to decide which action to take like which canal patch to move to, how much sediment to deposit, and how much to resuspend. The model is driven by the sediment agents traveling through the canal network.

The canal patches have five state variables: sediment depth (h_s), elevation, patch type, canal type, and canal name. The patch type indicates whether the patch is a canal patch or land patch. The canal type indicates whether it is a major or minor canal. Once cell represents 50 m^2 in the real canal system; this is calibrated to the results of the Osman (2015) study.

Time Scale

The model is based on a daily time step where one tick is equivalent to one day, and 365 ticks total one year.

3.3 GSAB Model Process Overview and Scheduling

The model process and scheduling shows patterns of sediment deposition and accumulation over time, given different values of the water flow rate, sediment concentration, offtake proportion, and management scenarios. The process of sediment transport, accumulation, and removal is modeled as follows:

1. Sediment Flow
    - The model simulates continuous sediment flow starting at the source of the flow at K57. The water flow is modeled as continuous uniform open channel flow at constant water level for trapezoidal channels, and the sediment are transported in suspension by the water. The Gezira Scheme was designed to have continuous water flow; therefore, the sediment flow is also continuous.
    - At each tick, sediment agents are created at the source of the flow (K57) with state variables calculated from Lacey equations used in the design of the Gezira Scheme (Equations 2.1, 2.2, and 2.3).

2. Sediment Transport
    - The sediment agents flow from high elevation patches to lower elevation patches, mimicking gravity flow. The sediment agents assess the elevation and amount of sediment in neighboring patches and only move to the target patch if the elevation and sediment amount is less than the patch that it is currently on.
    - After the sediment agent decides to move to a target patch, it calculates the sediment discharge using a mass balance. The amount of sediment that the sediment agents carry to the next canal patch has to equal the original sediment amount plus the amount of resuspended sediment minus the amount deposited onto the canal patch.
    - Only a proportion of the sediment from the Zananda Major Canal can move into the minor canals. This proportion is defined by the *offtake-proportion* parameter.
        - The upper boundary of the *offtake-proportion* represents the function of the weir structures that control the flow into the minor canals. As sediment fill up the minor canals, the *offtake-proportion* decreases linearly and negatively to the amount of sediment in the minor canal. This simulates the blockage of flow into the minor canals as sediment are accumulated. With less available space in the canal due to excessive sediment accumulation, water and sediment flow into the minor canals is restricted.
3. Sediment Deposition and Maintenance
    - The sediment agents deposit a certain amount of sediment to the canal patch network, which is calculated based on the deposition flux. The deposition flux is determined by the settling velocity and sediment concentration. As the canal network accumulates sediment, the amount of sediment deposition gets increasingly limited. Once the sediment volume in a minor canal reaches full capacity, defined as the total volume of the minor canal up to the design water level, no additional sediment agents can enter the minor canal from the major canal. However, sediment agents that are already in the minor canal can continue to deposit sediment onto the canal patch network depending on the sediment fluxes and sediment budget.
    - The resuspension of sediment from the canal patch network depends on the rate of erosion and shear stress in relation to the critical bed shear stress.

- There are three options of maintenance scenarios: No maintenance, centralized, and ad hoc.
  - In the "no maintenance" scenario, the minor canals are not desilted; no sediment is removed from the minor canals.
  - Centralized maintenance refers to centrally managed maintenance operations. It occurred every two years between April and June when the canal system is closed (Osman, 2015).
  - Ad hoc maintenance refers to maintenance conducted in a decentralized manner by the tenants themselves. Ad hoc maintenance occurs at any time during the year whenever the tenants notice sediment piling up in the canals, causing a restriction of their water supply.

Scheduling

The scheduling of the processes outlined in the previous section occurs as follows at each time step:

1. The sediment agents execute the *create-sediment-flow* sub-model which creates sediment agents at the source of the flow at K57 in the Zananda Major Canal. The sediment agents perform the following calculations:
   - Calculate the water discharge (Q)
   - Calculate the sediment discharge (Qs) based on Q and the *sediment-concentration* parameters.
   - Calculate the cross-sectional area (*x-area*) using Equation 2.2 and Q. Also, calculate the bed slope using Equation 2.3, which is used to calculate its Chezy coefficient.
   - Calculate shear velocity using the water velocity and Chezy coefficient.
   - Calculate the shear stress using the shear velocity and water density.
   - Calculate the deposition flux (*deposition-flux*) and erosion flux (*erosion-flux*).
   - Calculate the amount of sediment (*sediment-volume*) the agent holds based on the *deposition-flux*, *x-area*, and dry sediment density.
   - Transfer the *sediment-volume* to the canal network patch that it is standing on; the sediment depth (*sediment-depth*) of the canal patch is equal to the *sediment-volume* of the sediment agent divided by the *cell-size*, which is the area of land that one canal patch represents in real dimensions.

2. The sediment agents execute the *transport-sediment* sub-model, where it assesses which canal patch to move to. The sediment agents perform the following actions:
   - Find the neighboring canal patch with the lowest elevation and sediment volume. If the elevation in the target patch is lower than the canal patch it is currently standing on, then the sediment agent moves to the target canal patch and determines the new Qs using a mass balance of the sediment budget [New Qs = Old Qs – (*deposition-flux* × *x-area*) + (*erosion-flux* × *x-area*)]
   - If the sediment agent is originally on a major canal patch and the target canal patch is any of the minor canal patches (this happens at the intersections between the major canal and any of the minor canals), then it can move onto the minor canal patch only a certain proportion of the time, determined by the *offtake-proportion.* This offtake proportion represents the flow control weir structures that are at the offtakes. It has a negative, linear relationship with amount of sediment already in the minor canal, simulating that less sediment can enter the canal as the sediment volume of the canal increases. Once the maximum volume of the minor canal is filled with sediment, no additional sediment agents are allowed to move into the minor canal.
   - If a sediment agent reaches the end of the Zananda Major Canal (at K16.7), it "dies," simulating water drainage from the major canal. Note that the minor canals do not have drainage, as it was designed not to have any drainage.
3. The sediment agents execute the *deposit-and-maintain-sediment* sub-model where it determines how much sediment to deposit onto the canal network. If the maintenance scenarios are switched on, the sediment deposited on the minor canal patches are removed based on the defined capacity of centralized or ad hoc maintenance (*central-maintenance-capacity* and *adhoc-maintenance-capacity*, respectively).
   - Sediment deposition is the amount of sediment that the sediment agents transfer onto the minor canal patches; it is based on the deposition flux, cross-sectional area, and dry sediment density.
   - During centralized maintenance, the amount of sediment removed is based on the *central-maintenance-capacity* parameter. This parameter represents the full capacity of management's desilting fleet to conduct sediment removal. For example, a *central-maintenance-capacity* of 100%

means that all the maintenance fleet and equipment are available to conduct maintenance so the maximum amount of sediment that the fleet can remove is expected to be desilted from the minor canals.

- During ad hoc maintenance, the amount of sediment removed is based on the *adhoc-maintenance-capacity* parameter. This parameter represents the number of tenants who are conducting the maintenance. For example, an *adhoc-maintenance-capacity* of 100% means that all of the tenants are conducting maintenance. According to a Sudanese expert currently working on the Gezira Scheme, tenants did not maintain a desilting schedule; rather, they conducted maintenance only under emergency conditions when they notice sedimentation getting worse.

To summarize, the simplified model narrative is as follows:
Setup:

1. Set up canal network with elevation data
2. Set up water flow at the start of the Zananda Major Canal
3. Set up output results file

Go:

1. Create continuous sediment flow by creating new sediment agents at K57
2. Transport sediment agents downstream, mimicking gravity flow. Limit the inflow of sediment agents from the major canal into the minor canals based on the *offtake-proportion*
3. Deposit sediment and perform maintenance, if applicable

3.4 GSAB Model Design Concepts

This section details the model design concepts as outlined by the ODD+D protocol from Müller et al. (2013).

Theoretical and Empirical Background

The model is based on the physical processes of cohesive sediment transport. The equations used to determine the decisions of the sediment agents are from water flow and sediment dynamics theories related to uniform flow though trapezoidal cross sectional channels, settling of sediment, and sediment accumulation. The model was calibrated using empirical data from Osman (2015).

Emergence

Over time, different management scenarios and variations in input parameters (e.g., water discharge, offtake proportion, and sediment concentration) are expected to influence a pattern of sediment accumulation. When the sediment agents look for a neighboring patch of lower elevation to move to, the sediment agents closer to the center of the canals have more options of neighboring patches with lower elevation compared to sediment agents located at the edges. Once the sediment agent moves to a canal patch that borders the land patches, it is likely that the sediment agent will continue to move along the edge of the canal instead of moving back to the center. This gives rise to emerging behavior of the sediment where they start to move towards the edges; this mimics the narrowing of the cross section of the canal as sediment are transported within a canal.

Agent Adaptation, Decision-making, Learning, Prediction, and Sensing

The sediment agents make an individual decision regarding which patch to move to based on the elevation of the patches and the offtake proportion. Other than this, they do not adapt, learn, predict, or sense throughout the simulation.

Interactions

The sediment agents interact directly with the canal network. This interaction is dependent on the water flow, canal dimensions, and sediment concentration. In addition, sediment characteristics like the critical shear stress for erosion and deposition, dry sediment density, and erosion rate affect the amount of sediment that agents transfer onto the canal patches to mimic sediment deposition. The erosion flux impacts the amount of sediment the sediment agents resuspend from the canal network.

Stochasticity

The offtake proportion that regulates the movement of sediment agents from the major canal to the minor canals introduces some randomness into the model; the sediment agents are allowed to move into the minor canal from the Zananda Major Canal only if a randomly generated number between zero and 100 is less than the offtake proportion. This limits the number of sediment agents moving into the minor canal from the major canal, which represents the weirs controlling the water inflow into the minor canals. In other words, the sediment agents show randomness in their choice to move into the minor canals from the major canal based on a probability (the offtake proportion) of them moving into the minor canal from the major canal. This offtake proportion is dependent on the sediment already accumulated in the canal; if the minor canal is filled, fewer sediment agents are allowed to enter. The continuity of sediment flow is expressed as a probability of sediment agents' choice to move from the major canal to any of the minor canal. If the sediment agent chooses not to move, it stays in the major canal.

Collectives

There are no collectives, so there is no collective learning.

Observation

At each time step, the following data is collected:

- Sediment deposition in the major canal
- Sediment deposition in each of the seven minor canals
- Volume of sediment desilted from each of the seven minor canals
- Number of sediment agents on major and minor canal patches

3.5 GSAB Model Details

3.5.1 Model Assumptions

This section describes the assumptions used in the design of the GSAB Model.

Landscape-Driven Effects

The GSAB Model uses the sediment concentration parameter as a representation of increased sediment load into the system due to erosion from upstream regions like Ethiopia. Since the focus of the model is to understand the impact of management changes in maintenance, the landscape-driven effects of the surrounding area can be considered negligible. Given that erosion's influence on sediment is not straightforward and can be influenced by other factors like soil type and vegetation (Lesschen et al., 2009; Hooke, 2003), increasing the sediment concentration is the simplest way to simulate the impact of erosion on the system.

Hydrological Processes

The hydrological processes for the GSAB Model are represented indirectly by the sediment agents. The *water-flow-major* parameter, the water flow rate in the major canal, is assumed to be constant throughout the simulation, as this was the intended design of the Gezira Scheme. This means that the water flow does not change with the season. Because the expected time scale of sediment accumulation in the minor canals is years and not months, the variation of water flow within the year is ignored. The water flow rate, along with the sediment concentration determines the sediment discharge (Q_s).

The GSAB Model uses the *offtake-proportion* parameter to control the inflow of sediment agents from the major canal into the minor canals. This is proxy of water flow, as the GSAB Model indirectly depicts water flow with the sediment agents. A high (low) offtake proportion means that more (fewer) sediment agents can enter the minor canals. Because sediment are transported by water (see Section 2.1.2), reducing (increasing) the entrance of sediment agents into the minor canals represents a(n) decrease (increase) in water flow (Q).

Sedimentation Processes

Sediment transport depends on the water flow and sediment concentration (Mouri et al., 2014). The sediment type of the Gezira Scheme is fine sediment; therefore, the model ignores bed load sedimentation (Plusquellec, 1990). The values for dry sediment density, erosion rate, and critical shear stresses are determined based on values for silty sediment (Wallingford, 1990). The highest rate of siltation occurs in the minor canals, so the sediment accumulation and maintenance analyses focus on the minor canals (Wallingford, 1990; Plusquellec, 1990).

The sedimentation process represented in the model assumes that there is no overflow of sediment beyond the canal dimensions calculated from empirical data by Osman (2015). It assumes that all the minor canals have the same canal dimensions, since there is a lack of data on the exact dimensions. While real world evidence shows sediment overflowing the canal banks, the model assumes that sediment agents can only stay within the boundaries of the canal and that the inflow of sediment stops when the canal is full.

Operations and Management Structure

In the Gezira Scheme, upstream control structures maintain the water level in the irrigation system; historically, there is no systematic adjustment of flow release of the control structures (Osman, 2015). The model assumes that the night storage system in the Gezira Scheme is not in operation, as it is not used today. In addition, the GSAB Model assumes that the weir control structures at the offtakes of the Zananda Major Canal that regulate water and sediment inflow into the minor canals are functioning as intended. The GSAB Model assumes a constant water discharge and unchanging water levels, as was intended with Lacey's regime theory design (see Sections 2.2 and 3.3). However, the operation of the weirs is sensitive to sediment deposition in the minor canals and fluctuations in water level (Osman, 2015). Yet, the GSAB Model assumes that the weirs are operational according to the intended Lacey regime theory design.

Because of unreliable dredging records (Osman, 2015), the amount of silt removal is not based on actual empirical data of sediment removal but rather determined by the capacity of management's fleet for centralized maintenance. For ad hoc maintenance, the sediment removal is determined based on an estimated amount of sediment that one person can remove in one day. Woodson (2010) cites studies from Erasmus (1956) and Mabry (2008) where they assume one person can remove three cubic meters of dirt per day.

3.5.2 Initialization

Using Windows 11 Home and Netlogo version 6.2.2 (Willensky, 2021), sediment transport and deposition are implemented using two entities (sediment agents and canal network patches) to represent the Gezira Scheme in the Netlogo model world (Figure 3.2). The darker blue patches in Figure 3.2 indicate the Zananda Major Canal, and the lighter blue patches indicate the minor canals that offtake from the Zananda Major Canal. There are seven minor canals in the model: G/Elhosh, Gimillia, Ballol, W/Elmahi, Toman, Gemoia, and G/Abu Gomri. Each patch has elevation data taken from Google Earth Pro version 7.3. The data from Google Earth Pro was searched in the GPS Visualizer (Schneider, 2019). The length of the canals is scaled so that 10 patches represent one kilometer. The green patches indicate land. In the model, the sediment agents can only move onto other canal patches; it cannot move onto land patches. In one tick, sediment agents move one patch at a time. Because the sediment agent themselves contain state variables like the cross sectional area and bed slope, the movement of the sediment agent from one patch to the next does not represent the water velocity; rather, the water velocity is calculated by the sediment agents themselves based on the sediment budget and the changing characteristics of the canal. The scaling factor relates the sediment volume carried by the sediment agent to the real system. This allows for the sediment agent to move in a way that mimics gravity flow while adjusting the water and sediment discharge rate according to the sediment budget. Each tick represents one day.

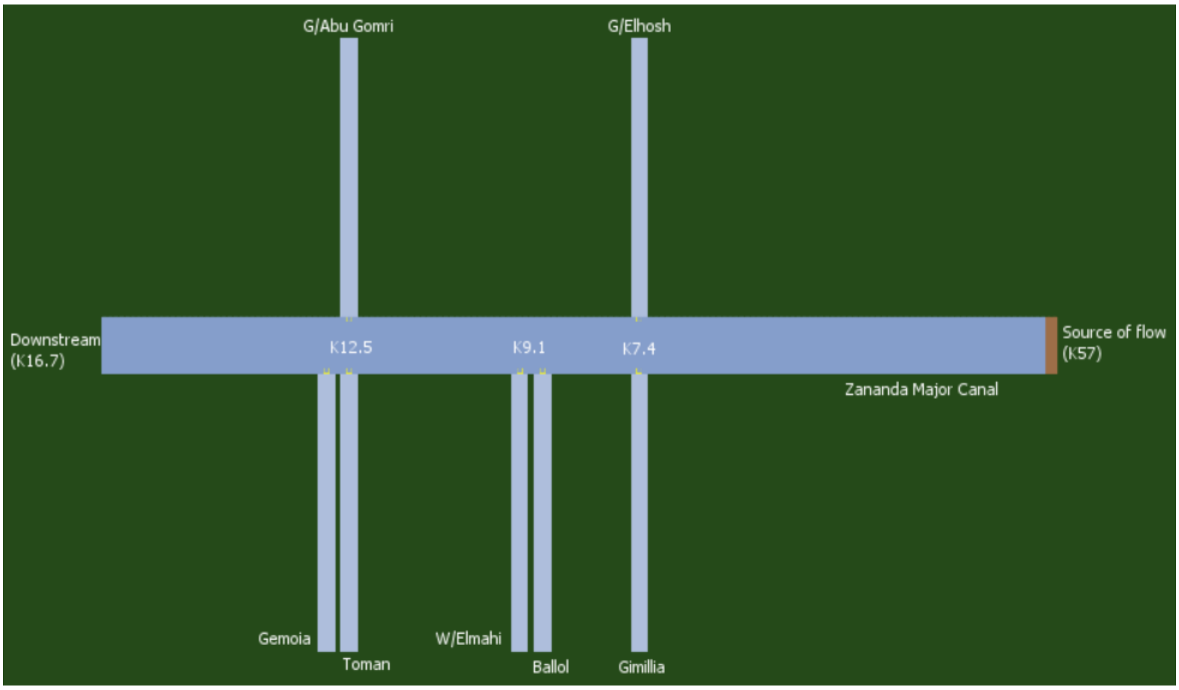


Figure 3.2: Netlogo model world setup.

The total length of the Zananda Major Canal is 16.7 km, and each minor canal is 4.8 km long (Osman, 2015). The minor canals are modeled as trapezoidal channels with a cross-sectional area of 1.36 m^2 (Osman, 2015). At the start of the simulation, the minor canals are empty; sediment agents are only placed on the Zananda Major Canal. This reflects the real-world situation where the minor canals were empty upon completion of the Gezira Scheme in the 1920s. Water and sediment enter the minor canals from the major canal only when the canal was opened.

3.5.3 Input Parameters

The source of the flow starts at K57 in the Zananda Major Canal as indicated in Figure 3.2. The sediment agents flow downstream, from K57 to K16.7. With the intended Lacey regime theory design, the initial conditions of the sediment agents are shown in Table 3.1. The rest of this section will use the values for the intended design as an illustration of the calculations performed in the model.

Parameter	Units	Value	Description	References
Q	m^3/s	3.52	Design water discharge of the Zananda Major Canal	Osman, 2015; Osman et al., 2017; Ali, 2020
ρ_w	kg/m^3	1000	Density of water	Osman, 2015
ρ_s	kg/m^3	1200	Dry sediment density of the silt deposits taken from previous studies of the Blue Nile River.	Ali, 2014; Osman et al., 2016
c_s	kg/m^3	6	Sediment concentration in the Zananda Major Canal.[a]	Osman, 2015; Theol et al., 2019
$o_{\%}$	%	13	The offtake proportion. The probability that a sediment agent decides to move from a Major Canal patch to any of the minor canals, simulating the restriction of inflow to the minor canal as sediment accumulate. 13% is the flow restriction of the intended design.	Osman, 2015
τ_d	N/m^2	0.078	Critical shear stress for deposition. This is a typical value for sediment concentrations from 3,000-10,000 ppm.	Krone, 1962
τ_e	N/m^2	0.10	Critical shear stress for erosion	Osman, 2015
M	$kg/m^2/s$	0.0016	Rate of erosion of fine sediment	Osman et al., 2016
$h_{s,\%}$	%	70	The percent of the maximum sediment depth that triggers ad hoc maintenance. This is a proxy for when tenants notice the sedimentation is worsening. The max depth in the minor canals is determined by the $V_{max,minor}$ (Equation 3.13) divided by the number of patches in one minor canal, divided by the *cell-size*.[b]	Assumption
cap_c	%	100	The capacity of centralized management to conduct maintenance.[b]	Assumption
cap_a	%	100	The capacity of tenants to conduct maintenance.[b]	Assumption

Table 3.1: GSAB Model input parameters based on the intended Gezira design.

[a] 6 kg/m^3 is the concentration used by Osman (2015). Theol et al. (2019) uses the Osman (2015) study for model calibration and verification; in it, they use a conversion of 1000 ppm to 1 kg per m^3 for the sediment concentration. Osman (2015) uses a constant concentration of 6,000 ppm which is equal to 6 kg/m^3 with this conversion rate.

[b] These maintenance-related parameters are further detailed in Section 3.6.3.

3.6 GSAB Model: Sub-models

There are three sub-models in the GSAB Model: 1) *create-sediment-flow*, 2) *transport-sediment*, and 3) *deposit-and-maintain-sediment*.

3.6.1 Sub-model 1: Create continuous sediment flow

This sub-model simulates continuous flow by creating a constant number of sediment agents at the source of the flow (K57). In this sub-model, the sediment agents determine their initial condition by calculating the following state variables: Q, Q_s, A, S_0, E, and D. Note that the sediment volume (V_s) is calculated in Sub-model 3 (Section 3.6.3).

Water discharge (Q)

The water discharge (Q) is determined by the input parameter in the GSAB Model. The default Q is 3.52 m^3/s; this is the water flow rate used in the Lacey regime theory design of the Gezira canal system (see Table 3.1).

Sediment discharge (Q_s)

The sediment discharge (Q_s) is based on the water discharge (Q), as shown in Equation 3.1. With the design conditions of $Q = 3.52\ m^3/s$ and $c_s = 6\ kg/m^3$, the Q_s is $21.12\ kg/s$. In the GSAB Model, the Q and Q_s are scaled by the *scale-factor* which was determined empirically to calibrate the model to results by the Osman (2015) study.

$$Q_s = Q \cdot c_s \tag{3.1}$$

Cross sectional area (A) and Bed slope (S_0)

Using the Lacey equations, the cross-sectional area and bed slope are calculated by the sediment agents. The results are in Table 3.2.

Parameter	Units	Value	Description	Reference
A	m^2	7.42	Cross-sectional area calculated by Equation 2.2 where $K_a = 2.6$	Matthews, 1952; Gismalla, 2009
S_0	cm/km	11.27	Bed slope calculated by Equation 2.3 where $K_s = 13.9$. *Note: the equivalent dimensionless bed slope is 0.00011.*	Matthews, 1952; Gismalla, 2009

Table 3.2: Cross sectional area and bed slope calculated with Lacey equations that were used to design the Gezira canals according to Lacey's regime theory method (Lacey, 1930).

Erosion flux (E)

The water velocity, Chezy friction coefficient, shear velocity, and shear stress are needed to determine the erosion flux. First, the water velocity is determined by dividing the cross sectional area calculated in Table 3.2 by the water discharge (Q).

$$U = \frac{Q}{A} \tag{3.2}$$

where:
U = Water velocity [m/s]
Q = Water discharge [m^3/s]
A = Cross-sectional area [m^2]

Then, the Chezy friction coefficient is calculated using Equation 3.3 from Mendez (1998) and Winterwerp et al. (2022).

$$C = \frac{U}{\sqrt{S_f \cdot R}} \tag{3.3}$$

where:
C = Chezy coefficient [m$^{0.5}$/s]
S_f = energy slope [-] = bed slope, S_0, in uniform flow (Osman, 2015)
R = hydraulic radius [m]

The hydraulic radius is the cross sectional area divided by the wetted perimeter (P). The wetted perimeter is determined by Equation 2.1 where $K_p = 5.51$ (Gismalla, 2009). The shear velocity ($u*$) is determined by Equation 3.4 (Winterwerp et al., 2022).

$$\frac{u*}{U} = \frac{\sqrt{g}}{C} \tag{3.4}$$

where:
$u*$ = shear velocity [m/s]
U = water velocity [m/s]
C = Chezy coefficient [m$^{0.5}$/s]
g = gravity acceleration = 9.81 m/s^2

The bed shear stress (τ_b) is determined by Equation 3.5 where ρ_w is the density of water at 1000 kg/m^3 (Winterwerp et al., 2022).

$$\tau_b = u*^2 \cdot \rho_w \tag{3.5}$$

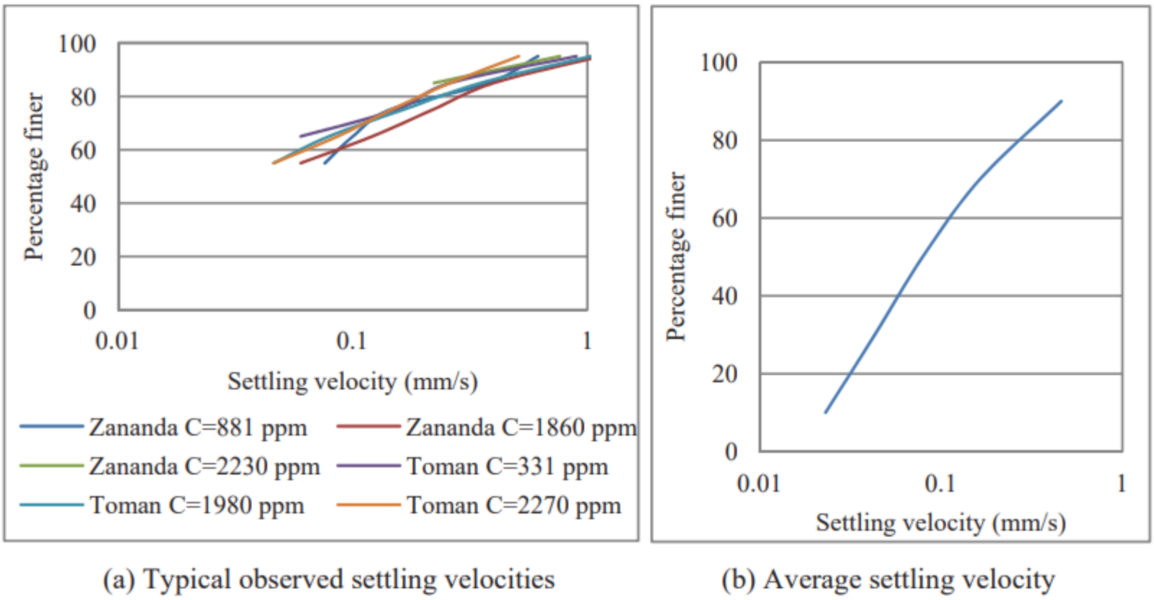
The erosion flux (E) is used to determine how much resuspension of sediment occurs based on on the bed shear stress. Equation 3.6 shows how the erosion flux is calculated (Partheniades, 1965).

$$E = M \cdot \left(\frac{\tau_b}{\tau_e} - 1 \right) \tag{3.6}$$

where:
E = erosion flux [kg/m^2/s]
M = resuspension rate [kg/m^2/s]
τ_e = critical shear stress for erosion [N/m^2]

The resuspension rate (M) is set to 0.0016 kg/m^2/s, as used in the study by Osman (2015) and other published results from Whitehouse et al. (2000) and Lumborg (2005). This resuspension rate is constant (Winterwerp and Van Kesteren, 2004). When the bed shear stress (τ_b) exceeds the critical shear stress for erosion (τ_e), erosion occurs. In this research, a critical shear stress for erosion at 0.1 N/m^2 is used; Osman (2015) determined this is the best fitting value for the measured bed profile in Gezira.

Deposition flux (D)
The deposition flux determines how much sediment is deposited based on the settling velocity. Wallingford (1990) measured the settling velocities of various suspended sediment concentrations in the Zananda Major and Toman Minor Canals; Osman (2015) plots the results as shown in Figure 3.3.



(a) Typical observed settling velocities (b) Average settling velocity

Figure 3.3: Settling velocities measured in the Wallingford (1990) study and plotted by Osman (2015).

Using these results, Osman (2015) finds a correlation between the measured settling velocity and sediment concentration in the Zananda Major Canal as shown in Figure 3.4.

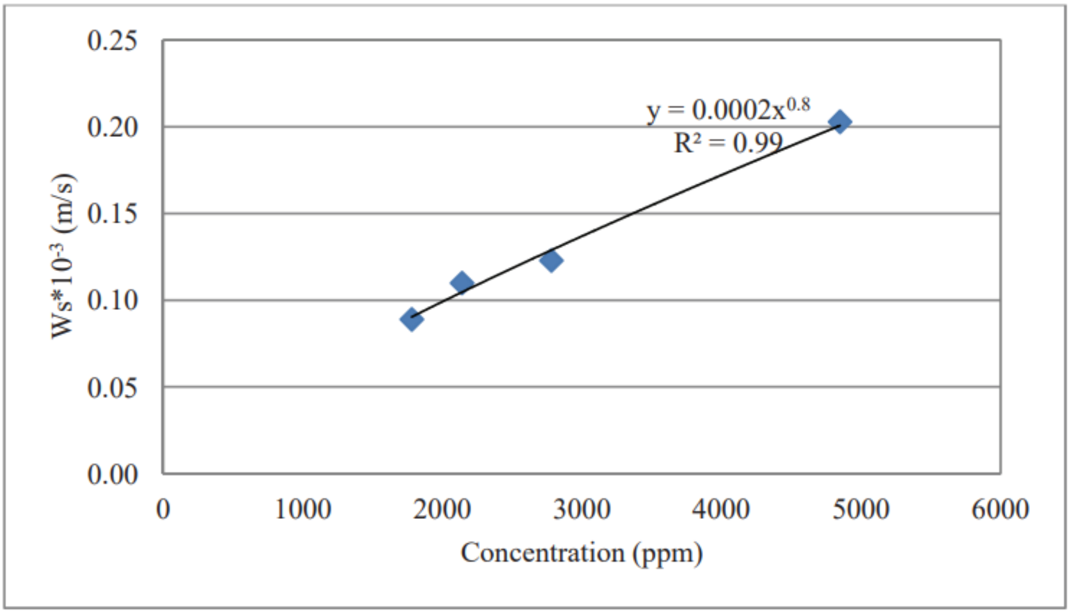


Figure 3.4: Relationship between settling velocity and sediment concentration in the Zananda Major Canal (Osman, 2015).

Using Figure 3.4, Osman (2015) derives Equation 3.7 for the settling velocity.

$$w_s = 2 \times 10^{-7} \cdot c_{s,ppm}^{0.8} \tag{3.7}$$

where:

w_s = settling velocity [m/s]

$c_{s,ppm}$ = sediment concentration [ppm]

At a constant sediment concentration of 6,000 ppm, the settling velocity is 0.00021 m/s or 0.21 mm/s. The deposition flux (D) in kg/m^2/s is calculated using Equation 3.8 (Winterwerp et al., 2022).

$$D = w_s \cdot c_s \tag{3.8}$$

To illustrate the cadence of calculations, Table 3.3 shows results of the initial setup using input data from Section 3.5.3.

Parameter	Units	Value	Source
Q	m^3/s	3.52	Table 3.1
c_s	kg/m^3	6	Table 3.1
U	m/s	0.47	Equation 3.2 and Table 3.2
C	m$^{0.5}$/s	52.7	Equation 3.3 and Tables 3.1 & 3.2
Q_s	kg/s	21.12	Equation 3.1
$u*$	m/s	0.028	Equation 3.4
τ_b	N/m^2	0.79	Equation 3.5
w_s	m/s	0.00021	Equation 3.7
D	kg/m^2/s	0.00126	Equation 3.8
E	kg/m^2/s	0.011	Equation 3.6

Table 3.3: Values of the initial setup under design conditions for Sub-model #1.

3.6.2 Sub-model 2: Transport sediment

Sediment in the Gezira Scheme is transported in suspension (Osman et al., 2016) and considered cohesive sediment transport (Lawrence and Atkinson, 1998; Gismalla, 2009; Osman, 2015). Osman (2015) performed a water column test to see how fast the sediment settled. He finds that the sediment is homogenous in the water column and is mainly wash load. No flocculation was observed even at high concentrations. The flow and water level are constant throughout the system (Johnstone, 1929; Ministry of Irrigation and Hydro-Power, Sudan, 1934). The night storage system is not modeled as it is not in use today (Plusquellec, 1990).

At each tick, water agents move to a downstream, neighboring patch whose elevation plus sediment amount is less than that of itself; this mimics gravity flow. Q and Q_s are updated using sediment mass balance as shown in Equation 3.9.

$$Q_{s,new} = Q_s - D \cdot A + E \cdot A \tag{3.9}$$

If a sediment agent on the Zananda Major Canal identifies a minor canal patch to move to, the probability of it moving to the minor canal patch is equal to the offtake proportion. Under design conditions, the maximum offtake proportion is 13%. The 13% proportion was taken from the study by Osman (2015) that finds the flow capacity of the minor canals to be approximately 13% of the Zananda Major Canal. The randomness introduced by the offtake proportion simulates the weirs at the offtakes to the minor canals that control the water flow and therefore, the sediment flow into the minor canals. It also maintains continuity of sediment flow should the sediment agent decide not to move into the minor canal patch. The offtake proportion into each of the minor canals is determined based on the sediment volume already in the minor canal. This is shown in Equation 3.10, where the GSAB Model assumes that there is a linear and negative relationship between the maximum offtake proportion and the volume of sediment in the minor canal.

$$o_{\%,i} = \frac{-o_{\%,max}}{V_{max,minor}} \cdot V_{s,i} + o_{\%,max} \tag{3.10}$$

where:
$o_{\%,i}$ = offtake proportion [%] for minor canal i
$o_{\%,max}$ = max offtake proportion [%]; 13% is the intended design
$V_{max,minor}$ = max volume of the minor canal [m^3] based on canal dimensions up to the design water level (Osman, 2015)
$V_{s,i}$ = volume of sediment in minor canal i

Equation 3.10 ensures that the upper boundary of the offtake proportion occurs when the total sediment deposition in the minor canal is zero. Conversely, the lower boundary of the offtake proportion, when it equals zero, occurs when the sediment volume in the minor canal is at its maximum.

Using Lacey's equation for the cross sectional area (Equation 2.2) and the design discharge of 0.46 m^3/s for minor canals, the cross sectional area was found as shown in Equation 3.11.

$$A = 2.6 \times 0.46^{\frac{5}{6}} = 1.36m^2 \tag{3.11}$$

Using the equation for the area of the trapezoid, the depth is calculated according to Equation 3.12 using an average top width of 6 m and bottom width of 1 m (Osman, 2015).

$$A = 1.36m^2 = \frac{1}{2}(1m + 6m) \times h \rightarrow h = 0.389m \tag{3.12}$$

The total volume, $V_{max,minor}$, is calculated according to Equation 3.13 with the length of a minor canal set to 4,800 m (Osman, 2015).

$$V_{max,minor} = \frac{1}{2}(1m + 6m) \times 0.389m \times 4800m = 6535.2m^3 \tag{3.13}$$

The red arrows in Figure 3.5 show the potential pathways that sediment agents can take as they flow downstream starting from the flow source at K57.

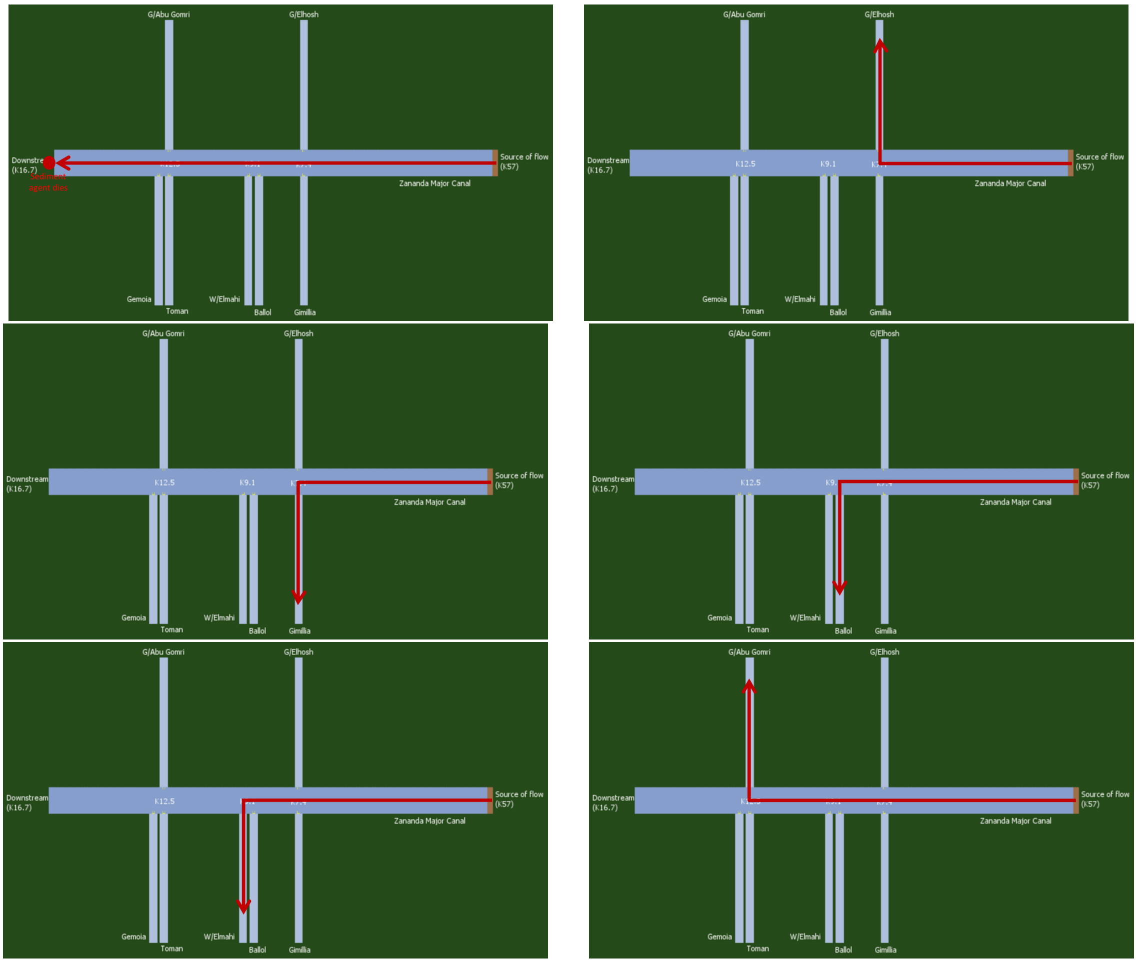


Figure 3.5: Potential routes sediment agents can take in the GSAB Model. Note that sediment agents that reach K16.7 die, simulating drainage from the Zananda Major Canal. Sediment agents that enter the minor canals will stay there throughout the simulation. The only way to remove sediment from the minor canals is to remove it through maintenance.

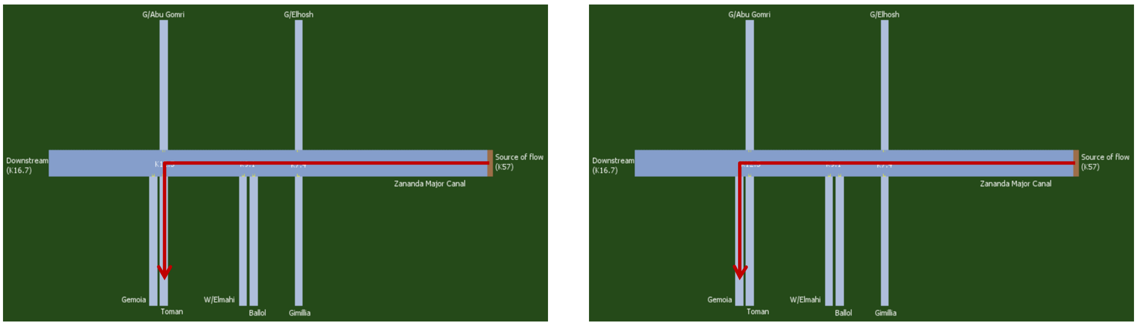


Figure 3.5: Potential routes sediment agents can take in the GSAB Model (continued).

3.6.3 Sub-model 3: Deposit sediment and conduct maintenance

Sediment deposition

To model sediment deposition, sediment agents transfer sediment that they do not carry to the next patch onto the canal patch network. The sediment volume that each water agent deposits onto the canal network is calculated by the Equation 3.14.

$$V_s = \frac{D \cdot A}{\rho_s} \tag{3.14}$$

where:

V_s = volume of sediment [m^3]

D = deposition flux [kg/m^2/s]

A = cross-sectional area [m^2]

ρ_s = dry sediment density [kg/m^3] = 1200 kg/m^3 (Osman, 2015)

The canal patches accumulate sediment according to Equation 3.15.

$$h_s = \frac{V_s}{\textit{cell-size}^2} + h_{s,existing} \tag{3.15}$$

where h_s = sediment depth [m] and $h_{s,existing}$ is the sediment depth that already exists on the patch. The *cell-size* is calibrated from the canal bottom area and scaled to the Netlogo model (see Section 3.7). The bed width (b) and side slope (m) of the Zananda Major Canal are set to 5 m and 1 (dimensionless), respectively (Osman (2015)). The cross-sectional area of a trapezoidal channel is determined by Equation 3.16.

$$A = (b + m \cdot h) \cdot h \tag{3.16}$$

where:
A = cross-sectional area [m^2]
b = bed width [m]
m = side slope [-]
h = water depth [m]

Centralized maintenance

According to Plusquellec (1990), the fleet of dredging machinery used by the EMC for desilting contains "64 draglines, 31 hydraulic excavators, 19 bulldozers, 12 elevated motorgraders, and 10 motorgraders." For the minor canals, only the hydraulic excavators, elevated motorgraders, and regular motograders were used. The average output of the machinery in 1990 was between 7,000 to 10,000 m^3 per month per machine, which was much less than half the expected nominal output of 20,000 m^3 per month per machine (Plusquellec, 1990). This lower output is due to aging of machinery and lack of monitoring of its performance (Plusquellec, 1990).

As shown in Table 2.2, there are 1,498 minor canals in the Gezira Scheme. At full capacity of 20,000 m^3 per month per machine with 31 machines, the sediment removal capacity is 620,000 m^3 per month. In a given year when there is three months of desilting, the maximum capacity of the fleet is 1.86 million m^3. This means that for one minor canal, the total amount of sediment that can be removed at 100% capactiy is 1,241.66 m^3. Multiplying this number by seven, representing the seven minor canals in the GSAB Model, gives the full desilting capacity of the minor canals in the Zananda Major Canal command area which is 8,691.59 m^3 over three months in a given maintenance year. This means that in each time step or day at 100% capacity, 96.57 m^3 can be removed.

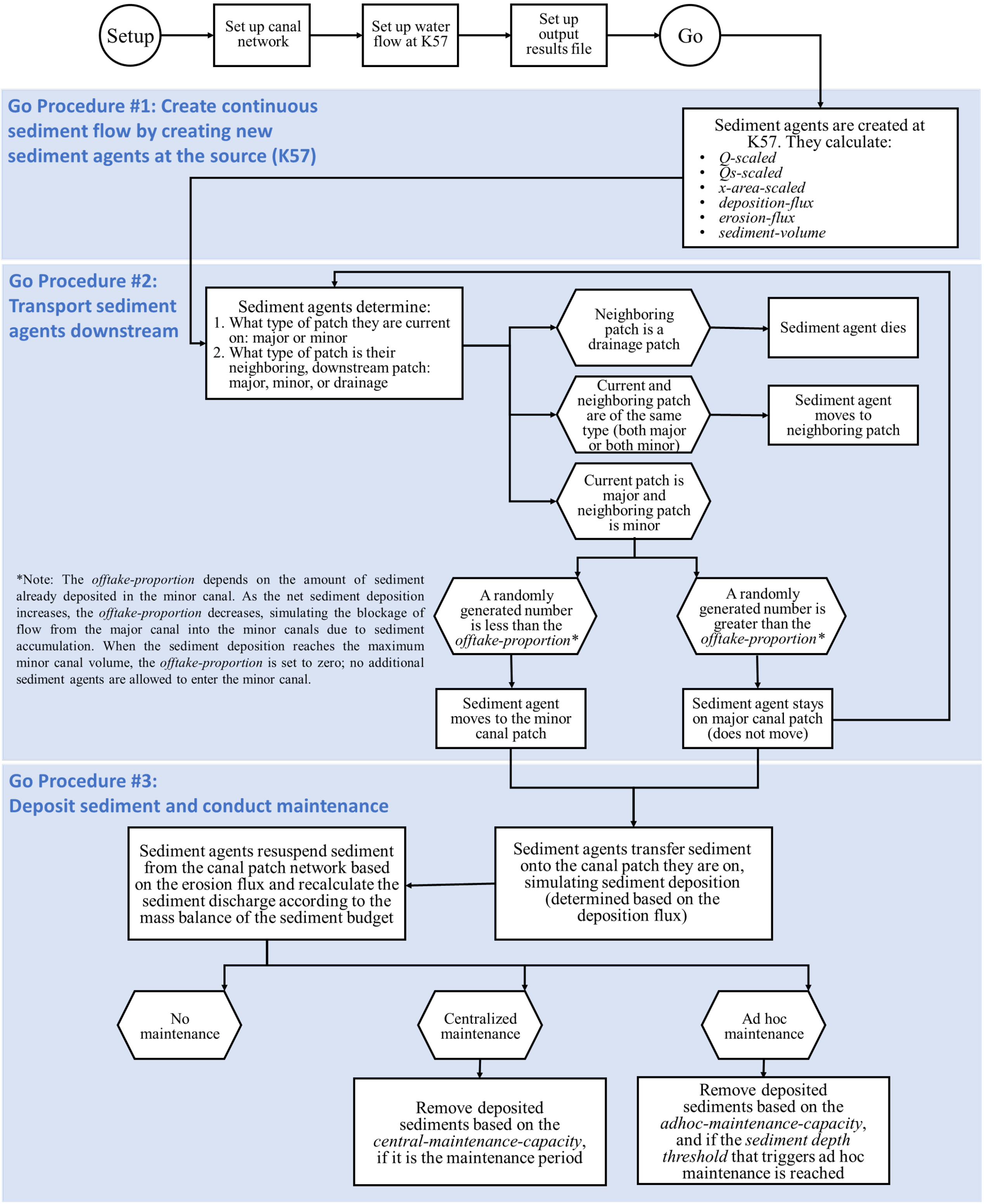
The GSAB Model allows for the user to switch on or off the maintenance activities for each individual minor canal. The capacity of the fleet is distributed among the minor canals that are switched on. For example, if two minor canals are switched on to have centralized maintenance conducted, the capacity of the fleet will be distributed between those two minor canals. In addition, the capacity of centralized maintenance can be adjusted to be anywhere between 0 to 100%. This adjusts the desilting capacity of the fleet between zero and the maximum full capacity of 96.57 m^3 per day. Every two years between the months of April and June, centralized maintenance is conducted where the sediment removed from the minor canal depends on the capacity of the fleet.

Ad hoc maintenance

The ad hoc maintenance represents maintenance conducted by tenants. Ad hoc maintenance activities can happen anytime throughout the year whenever the sediment depth reaches the user-defined sediment depth threshold ($h_{s,\%}$). This threshold represents the sediment depth at which tenants notice that there is too much sediment accumulation, so they start to desilt. It is a proxy of how often desilting happens during ad hoc maintenance. According to a Sudanese expert currently working on the Gezira Scheme, when maintenance responsibilities were transferred from centralized maintenance to the tenants, operational responsibilities such as controlling when the canal system opens were also transferred. The tenants did not close the canals when they conducted maintenance. Therefore, the GSAB Model does not close the water and sediment flow into the minor canals during ad hoc maintenance to reflect what the tenants did historically.

According to Goelnitz and Al-Saidi (2020), there are 140,000 Gezira Scheme tenants. Given that the total command area of the Gezira Scheme is 880,000 ha and the command area of the Zananda Major Canal is 8,250 ha (see Table 2.3), the scaling factor between the Zananda Major Canal and the total area is 0.0097. Using this scaling factor, the approximate number of tenants that operate withing the command area of the Zananda Major Canal is 1,356. Assuming that one person can remove three cubic meters of sediment in one day (Woodson, 2010), the maximum amount of sediment the tenants can remove in one day is 4,068 m^3 from all seven minor canals. For one minor canal, the max amount tenants can remove in one day is 581.14 m^3. In the ad hoc case, the maximum amount of sediment removal cannot be distributed among the other minor canals if there is remaining capacity for desilting; this reflects the reality that tenants only desilt the minor canal that is closest to them, the one that the rely on for irrigation. When the sediment depth reaches the threshold ($h_{s,\%}$), ad hoc maintenance is triggered where the amount of sediment removed is dependent on the capacity of ad hoc maintenance (cap_a), which represents the number of tenants conducting maintenance.

Note that there is no drainage from the minor canals, and sediment can only be removed through maintenance. This reflects the real conditions of the Gezira Scheme where the initial design of the minor canals did not include drainage. To summarize, Figure 3.6 shows the model process flow as detailed in this chapter.



*Note: The *offtake-proportion* depends on the amount of sediment already deposited in the minor canal. As the net sediment deposition increases, the *offtake-proportion* decreases, simulating the blockage of flow from the major canal into the minor canals due to sediment accumulation. When the sediment deposition reaches the maximum minor canal volume, the *offtake-proportion* is set to zero; no additional sediment agents are allowed to enter the minor canal.

Figure 3.6: GSAB Model flow diagram.
The circles indicate the start of an event while the rectangles denote the processes in the model. The hexagons determine the conditions that need to be fulfilled to continue down the pathway indicated by the arrows.

3.7 GSAB Model Calibration

The GSAB Model is calibrated by the results of the Osman (2015) study on the impact of maintenance on cohesive sediment transport in the Gezira Scheme. In the first reach of the Zananda Major Canal, which is the first 7.4 km of the canal, he found that with a 3.5 m^3/s water discharge, there was 157 m^3 of sediment deposition in three days. Given a bottom width of 5 m and a length of 7.4 km, the bottom area of the canal is 37,000 m^2. Therefore, the sediment depth throughout this first reach would be 4.24 mm. At this rate, the deposition for the entire 16.7 km Zananda Major Canal is 354.31 m^3 in three days. These results are used to calibrate the model to determine the appropriate *cell-size* and *scale-factor*. The *cell-size* and *scale-factor* were determined to be 50 m^2 and 31,000, respectively. The *cell-size* can be interpreted as a scaled bottom area, and the *scale-factor* scales the flow discharge, and therefore the sediment discharge, that each sediments agent carries. This simulates water and sediment transport without having to create a large number of sediment agents to represent each sediment grain.

3.8 GSAB Model Scenario Implementation

This section details the implementation of nine scenarios simulated over a period of 100 years that reflect various maintenance and environmental conditions, with a summary provided in Table 3.4. The 100-year simulation mimics the operation of the Gezira Scheme starting from its opening in the 1920s.

SIM #	Maintenance Strategy	Scenario Description
SIM-1	Centralized	Design conditions where Lacey's regime theory values are used for input parameters
SIM-2	Ad hoc	
SIM-3	Centralized	Increased sediment concentration due to erosion from upstream areas caused by overagriculture, population growth, drought, and deforestation
SIM-4	Ad hoc	
SIM-4.5	Ad hoc (at lower capacity)	
SIM-5	Centralized	Inadequate maintenance in the major canal causing a blockage of flow into the minor canals
SIM-6	Ad hoc	
SIM-7	Centralized	Increased inflow from the major canal caused by the Manaqil extension and increased water demand in the 1960s
SIM-8	Ad hoc	

Table 3.4: Summary of scenarios.

SIM-1: Centralized Reference Scenario

The centralized reference scenario represents the maintenance and environmental conditions before Sudan's independence when the Gezira system was thought to have been functioning as intended with centralized maintenance operating at full capacity (see Figure 2.2). Before World War II, all desilting equipment was available for maintenance, as it had not yet been repurposed for the war. Therefore, the centralized maintenance capacity is set to 100% while the model parameters are set to the values of the intended Lacey regime theory design. In addition, the inflow and outflow of sediment agents in the Zananda Major Canal is stable; this represents that there is adequate maintenance in the major canal such that there is no sediment accumulation in the major canal. Without sediment accumulation in the major canal, there is uninhibited flow from the major canal into the minor canal according to the offtake proportion ($o_{\%}$). Running this scenario for 100 years simulates the "ideal" situation if the full capacity of centralized maintenance and the intended design function of the system had continued to today. This simulation serves as the reference scenario to which other scenarios are compared.

SIM-2: Ad hoc Maintenance Scenario

The ad hoc scenario represents tenant-run, decentralized maintenance when operations and maintenance responsibilities were transferred to the WUAs (see Section 2.3.1 and Figure 2.2). In this scenario, maintenance can happen any time throughout the year whenever the tenants notice sediment accumulation because their water supply is disrupted. The GSAB Model was run for 100 years to simulate the state of the system if it had been maintained only by tenants since the canal system opened in the 1920s. Like SIM-1, the inflow and outflow of sediment in the major canal is stable throughout the simulation. This scenario is run with a 70% sediment depth threshold ($h_{s,\%}$) and 80% ad hoc maintenance capacity (cap_a). Setting the sediment depth threshold at 70% represents tenants waiting until emergency conditions, when the flow is noticeably disrupted by sediment accumulation, before starting to desilt (see Section 3.3). Setting the ad hoc capacity to 80% represents only 80% of tenants are available, able, and willing to desilt.

SIM-3: Increased Sediment Concentration with Centralized Maintenance

This scenario is intended to assess how well centralized maintenance can cope with an increase in sediment concentration. Erosion from upstream areas like the Ethiopian highlands beginning in the 2000s causes the sediment load into the Gezira canals to increase (see Table 2.7 and Figure 2.2). This scenario is similar to SIM-1 except the sediment concentration is increased from 6,000 ppm to 10,000 ppm.

SIM-4: Increased Sediment Concentration with Ad hoc Maintenance

Similar to SIM-3 but for ad hoc maintenance, this scenario is intended to assess how well tenant-run maintenance can cope with an increase in sediment concentration. The sediment concentration is increased to 10,000 ppm while keeping the ad hoc maintenance capacity at 80% and the sediment depth threshold at 70%.

SIM-4.5: Increased Sediment Concentration with Decreased Ad hoc Maintenance Capacity

SIM-4.5 is similar to SIM-4, except that the ad hoc maintenance capacity is reduced to 50%. This scenario is intended to assess the impact that a reduction in ad hoc maintenance capacity has on the net sediment deposition rate in the minor canals. It is likely that some tenants are unable or unwilling to help with maintenance. Therefore, comparing the results of this scenario with the previous scenarios shows how much the ad hoc maintenance capacity can be reduced while still maintaining a comparable amount of net sediment deposition in the minor canals. The sediment depth threshold is kept at 70%.

SIM-5: Inadequate Maintenance in the Major Canal with Centralized Maintenance in the Minor Canals

This scenario represents disrupted flow in the Zananda Major Canal due to sediment accumulation caused by inadequate maintenance in the major canal. When sediment accumulate in the major canal, less water can flow from the major canal to the minor canals. Because water carries sediment in suspension, less water flow from the major canal in the minor canals mean there is also less sediment entering the minor canals. In this scenario, the offtake proportion ($o_{\%}$) is halved from the design conditions to 6.5%. This represents reduced flow into the minor canals due to insufficient maintenance in the major canal. The minor canals are desilted with centralized maintenance.

SIM-6: Inadequate Maintenance in the Major Canal with Ad hoc Maintenance in the Minor Canals

This scenario is similar to SIM-5, except the minor canals are desilted by ad hoc, tenant-run maintenance. The ad hoc maintenance capacity and sediment depth threshold are set to 80% and 70%, respectively.

SIM-7: Increased Inflow from the Major Canal with Centralized Maintenance in the Minor Canals

This scenario represents an increase in water and sediment flow from the Zananda Major Canal into the minor canals. The higher inflow depicts the effect of the construction of the Manaqil Extension in the 1960s and higher water demand due to increased crop production (see Table 2.7 and Figure 2.2). To simulate an increase in water flow, the offtake proportion ($o_{\%}$) will double from its design value to 26%. The offtake proportion is a proxy of water and sediment flow entering the minor canals as it controls the amount of sediment agents that can enter (see Section 3.5.1). Doubling the offtake proportion will allow more sediment agents to flow from the major canal to the minor canals (see Section 3.3). The minor canals are desilted with 100% of the centralized maintenance capacity.

SIM-8: Increased Inflow from the Major Canal with Ad hoc Maintenance in the Minor Canals

This scenario is similar to SIM-7, except the minor canals are desilted by ad hoc, tenant-run maintenance. The ad hoc maintenance capacity and sediment depth threshold are set to 80% and 70%, respectively.

To summarize, Table 3.5 shows the input parameter values for each scenario.

Parameter	Units	SIM-1	SIM-2	SIM-3	SIM-4	SIM-4.5	SIM-5	SIM-6	SIM-7	SIM-8
Q	m^3/s	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52
ρ_s	kg/m^3	1200	1200	1200	1200	1200	1200	1200	1200	1200
c_s	ppm	6000	6000	10,000	10,000	10,000	6000	6000	6000	6000
$o_{\%}$	%	13	13	13	13	13	6.5	6.5	26	26
τ_d	N/m^2	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078
τ_e	N/m^2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
M	$kg/m^2/s$	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016
$h_{s,\%}$	%	N/A	70	N/A	70	70	N/A	70	N/A	70
cap_e	%	100	N/A	100	N/A	N/A	100	N/A	100	N/A
cap_a	%	N/A	80	N/A	80	50	N/A	80	N/A	80

Table 3.5: Input parameters for all scenarios.
Note: N/A means "not applicable."

In addition, simulations of sediment deposition without maintenance are performed under various environmental conditions to evaluate the sediment deposition rate and time it takes for the minor canals to be filled with sediment.

Chapter 4

Results: Gezira Sedimentation Agent-based (GSAB) Model Sensitivity Analysis and "No Maintenance" Simulations

4.1 GSAB Model Sensitivity Analysis

A global sensitivity analysis was conducted on the GSAB Model using NetLogo's BehaviorSpace and Python 3.8 to analyze the sensitivity of model parameters systematically. The global sensitivity analysis explores the effects of varying input parameters on the model output, discovering which input parameter has the biggest influence on the model results. The five input parameters that were assessed in the global sensitivity analysis are the sediment concentration (c_s), water flow (Q), capacity of centralized management to conduct maintenance (cap_c), capacity of tenants to conduct maintenance (cap_a), and the percent of the maximum sediment depth that triggers ad hoc maintenance ($h_{s,\%}$). These input parameters were varied according to Table 4.1 and simulated over five years.

Parameter	Min Value	Max Value	Varied by
c_s (ppm)	3000	10,000	1000
Q (m^3/s)	1.5	5.5	0.5
cap_c (%)	20	100	20
cap_a (%)	20	100	20
$h_{s,\%}$ (%)*	20	100	20

*Only for ad hoc maintenance scenarios.

Table 4.1: Varied parameters for the GSAB Model global sensitivity analysis.

4.1.1 Sensitivity Analysis of Water Flow and Sediment Concentration

The results of the global sensitivity analysis indicate that as water inflow and sediment concentration increases, the sediment deposition in the minor canals also increases (Figure 4.1). As discussed in Sections 3.3 and 3.6.3, sediment deposition is modeled by sediment agents transferring sediment that they do not carry to the next patch onto the canal patch network; the amount of sediment deposited is determined by the deposition flux, which is based on the settling velocity and sediment concentration. If sediment concentration is held at a constant value, an increase in the water inflow increases the sediment accumulation (Figure 4.2). Similarly, an increase in sediment concentration at constant water inflow also increases the sediment accumulation in the minor canals (Figure 4.3).

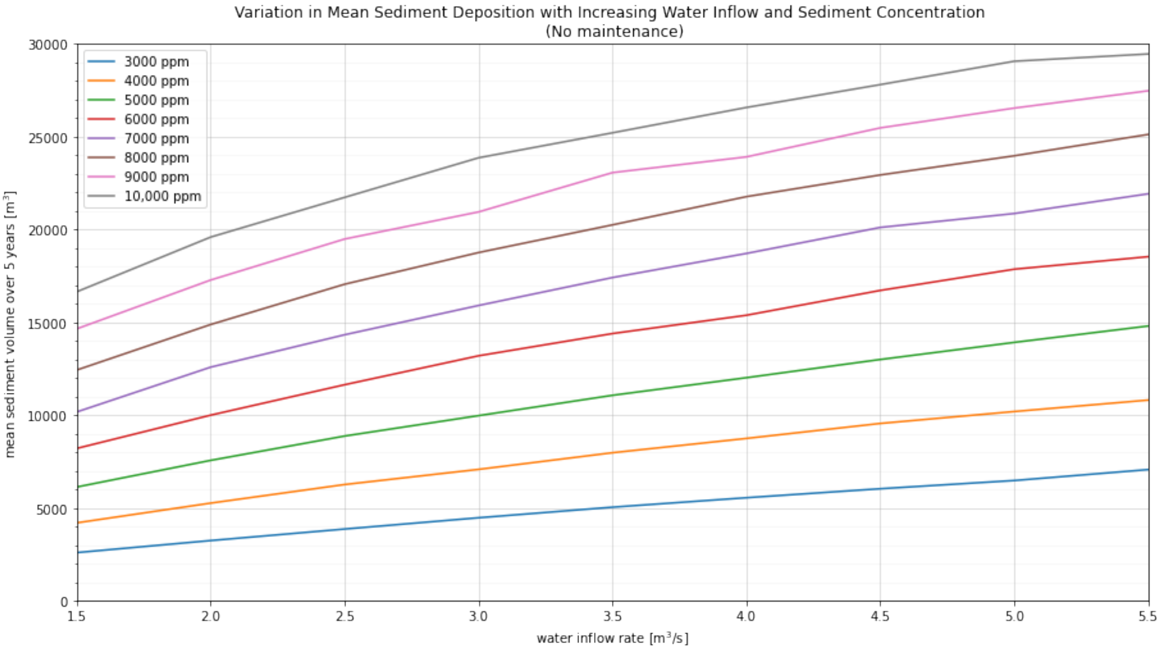


Figure 4.1: Sensitivity of the mean sediment deposition with varying Q & c_s in all minor canals over five years with no maintenance.

Figure 4.1 shows that the relationship between sediment concentration and sediment deposition is not linear; for example, doubling the sediment concentration does not double the resulting amount sediment deposition given a constant water inflow rate. This occurs for several reasons. First, the simulations for the sensitivity analyses span only five years. The minor canals at the beginning of the simulation are empty; this reflects the real-life situation where the canals were empty when the canal system was opened in the 1920s (see Section 3.5.2). Therefore, it takes time for the minor canals to fill up. This is shown by the increase in sediment deposition from the start of the simulation in Figures 4.2 and 4.3 as the simulation continues. The sediment agents need time from the start of the simulation to move from the major canal into the minor canals. This movement occurs based on the offtake proportion which regulates the flow of sediment agents into the minor canals (see Sections 3.3 and 3.6.2). The offtake proportion decreases linearly and negatively to the amount of sediment already in the minor canal (see Section 3.3). To illustrate, when the minor canal is empty, the offtake proportion is at its maximum value, which allows the maximum number of sediments to enter based on the weir's function. When the minor canal is filled up to its maximum volume with sediment, the offtake proportion becomes zero so that no additional sediment agents can enter the minor canals. This is to simulate the blockage of flow that occurs when sediment accumulates and clogs the minor canal. As the minor canals fill up over time, the inflow of sediment agents is restricted as there is less space for more sediment to enter.

Second, the amount of sediment that each agent deposits onto the canal patch network (V_s) is determined by the deposition flux (D); the deposition flux is linearly related to the amount of sediment deposited (see Equation 3.14 and Section 3.6.3). The deposition flux is equal to the settling velocity (w_s) multiplied by the sediment concentration (c_s), where the settling velocity equals $2 \times 10^{-7} \cdot c_{s,ppm}^{0.8}$ (see Equations 3.7 and 3.8). These relationships mean that volume of sediment deposition (V_s) is determined by the following equation where A is the cross-sectional area and ρ_s is the dry sediment density:

$$V_s = \frac{2 \times 10^{-7} \cdot c_{s,ppm}^{1.8} \cdot A}{\rho_s} \tag{4.1}$$

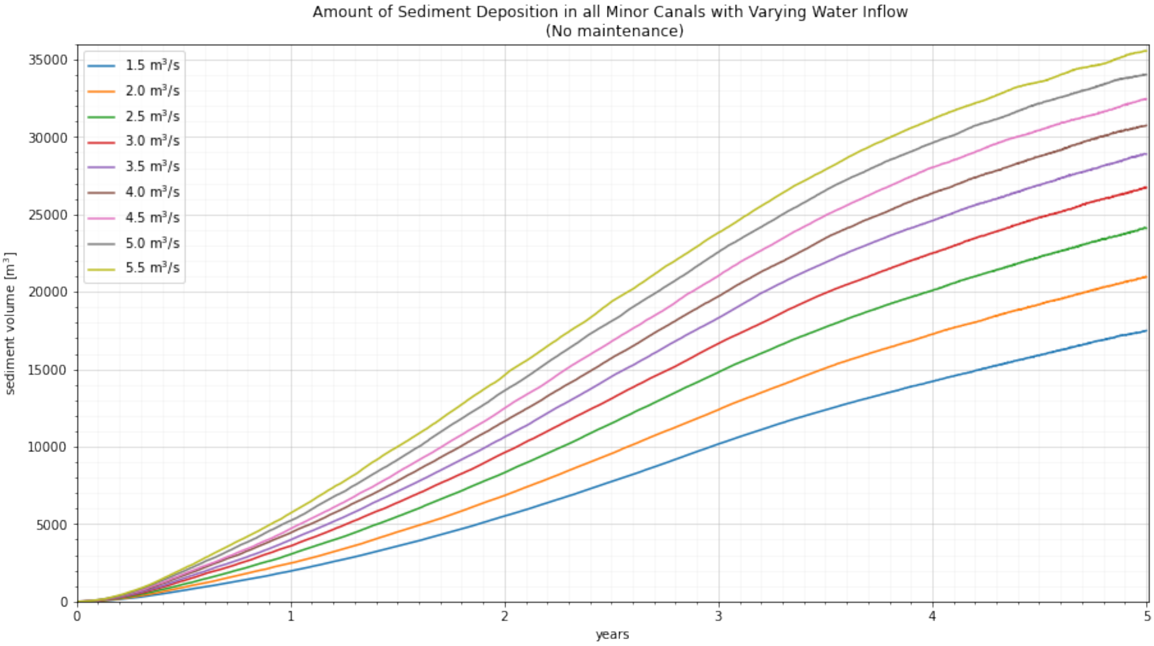


Figure 4.2: Amount of sediment deposition in the minor canals with varying Q and no maintenance.

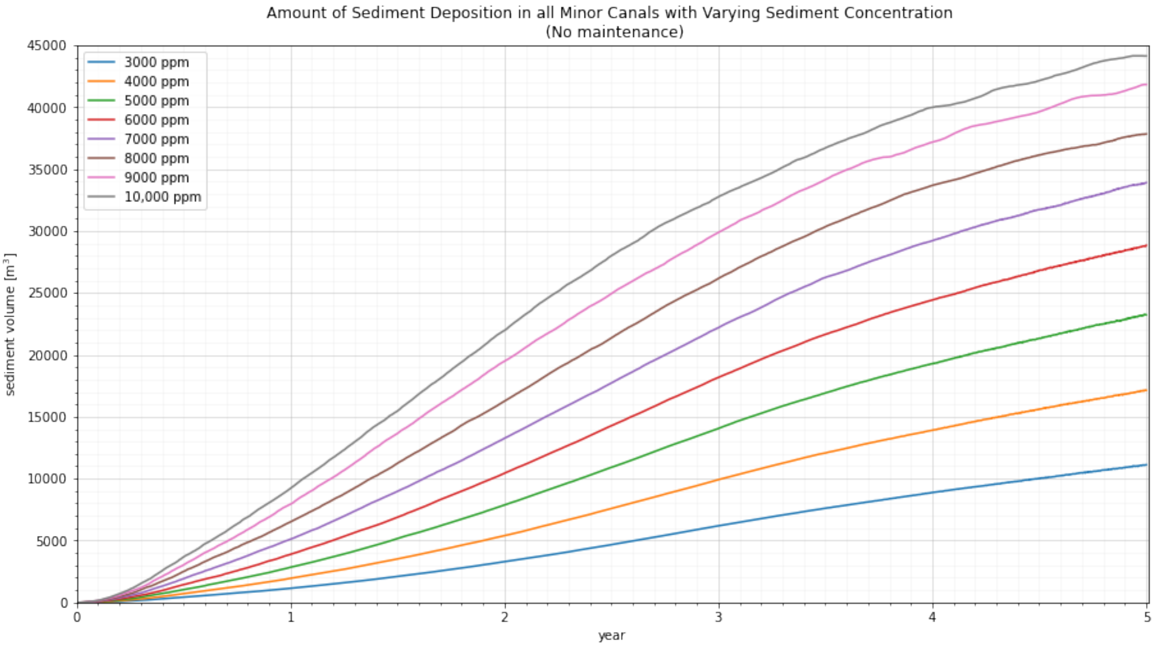


Figure 4.3: Amount of sediment deposition in the minor canals with varying c_s and no maintenance.

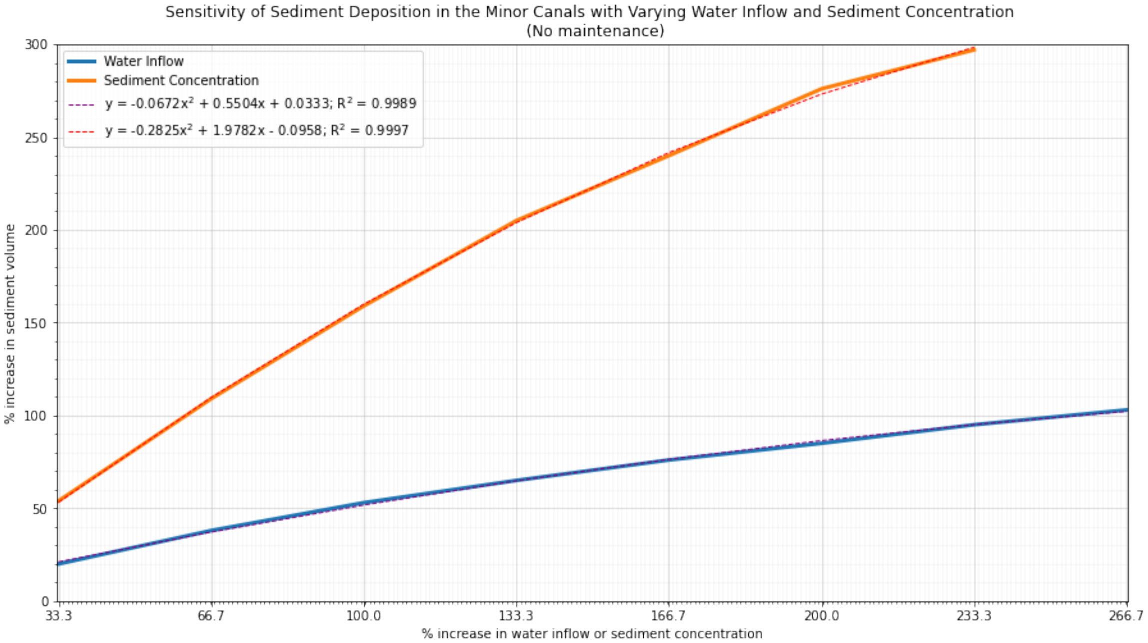


Figure 4.4: Sensitivity of sediment deposition with changes in Q versus c_s.

In the model world, sediment deposition in the minor canals is more sensitive to an increase in sediment concentration than water inflow (Figure 4.4). While a higher water discharge brings in more sediment into the minor canals, the sediment concentration drives sediment deposition, as it determines the deposition flux (Equation

4.1). This aligns with previous criticisms of the Lacey regime theory design of the canals that it does not consider the adequately sediment concentration, limiting the capacity of the canals to accommodate higher sediment loads (see Section 2.2).

At varying inflow and sediment concentration, the average percent of the minor canals filled with sediment is shown in Table 4.2. This further supports Figure 4.4 by showing that sediment accumulation is more sensitive to changes in sediment concentration than water inflow. Because the GSAB Model limits sediment accumulation to the maximum volume of the minor canal (see Section 3.3 and 3.6.2), the percentages in Table 4.2 can be determined. In reality, sediment could overflow from the designed dimensions of the canal; however, this is not modeled in the GSAB Model.

Water inflow (m^3/s)	Avg % of minor canal filled
1.5	38.2%
2.0	45.8%
2.5	52.7%
3.0	58.24%
3.5	63.2%
4.0	67.2%
4.5	70.9%
5.0	74.4%
5.5	77.7%

(a) Varying water inflow rates (Q).

Sediment concentration (ppm)	Avg % of minor canal filled
3000	24.3%
4000	37.5%
5000	50.8%
6000	63.0%
7000	74.1%
8000	82.7%
9000	91.4%
10,000	96.5%

(b) Varying sediment concentration (c_s).

Table 4.2: Percent of minor canals filled with sediment after five years with varying Q & c_s and no maintenance.

4.1.2 Sensitivity of Maintenance Capacity

The central maintenance capacity (cap_c), ad hoc maintenance capacity (cap_a), and sediment depth threshold ($h_{s,\%}$) were varied for the global sensitivity analysis while the water inflow and outflow in the Zananda Major Canal remains stable. The results of the global sensitivity analysis imply that central maintenance generates the least amount of sediment removal compared to all the ad hoc maintenance scenarios in absolute terms (Figure 4.5). In addition, the amount of desilted sediment is more sensitive to changes in maintenance capacity for ad hoc maintenance compared to centralized maintenance, particularly at lower sediment depth thresholds ($h_{s,\%}$). The GSAB Model triggers ad hoc maintenance to start earlier at lower sediment depth thresholds than higher ones; therefore, over time, sediment removal increases as the sediment depth threshold declines (see Appendix A.2 for further details).

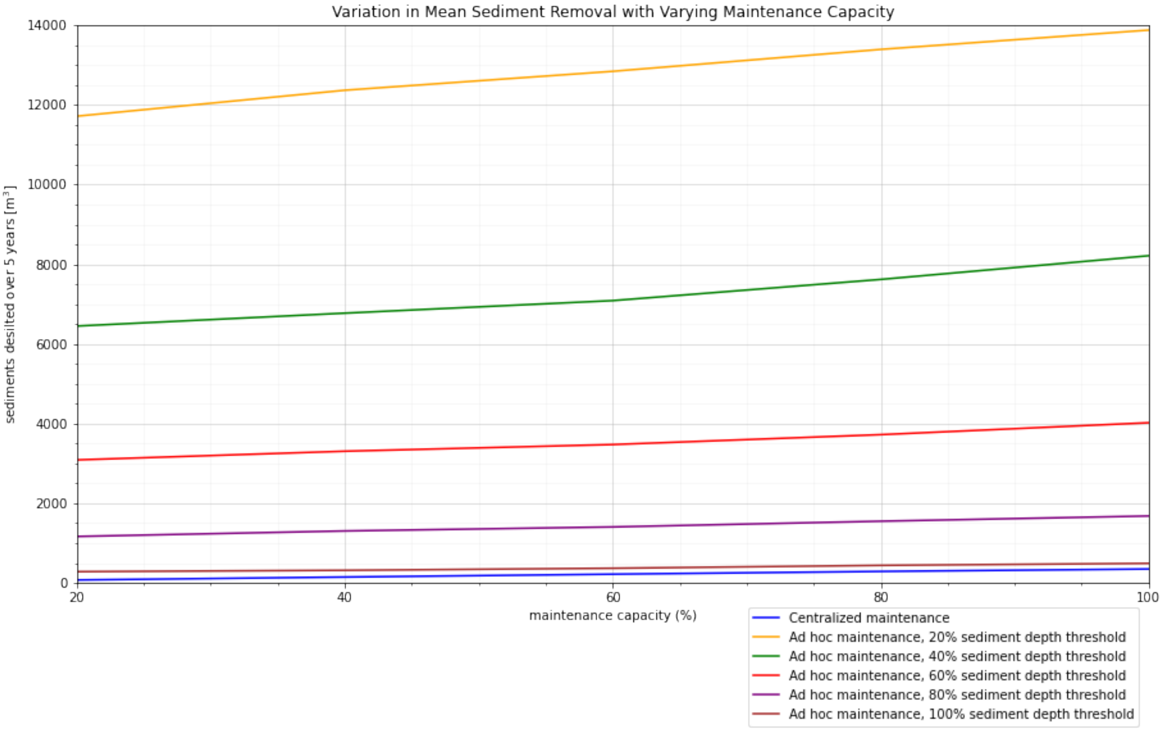


Figure 4.5: Sensitivity of sediment removal with varying maintenance capacity across all the minor canals over five years.

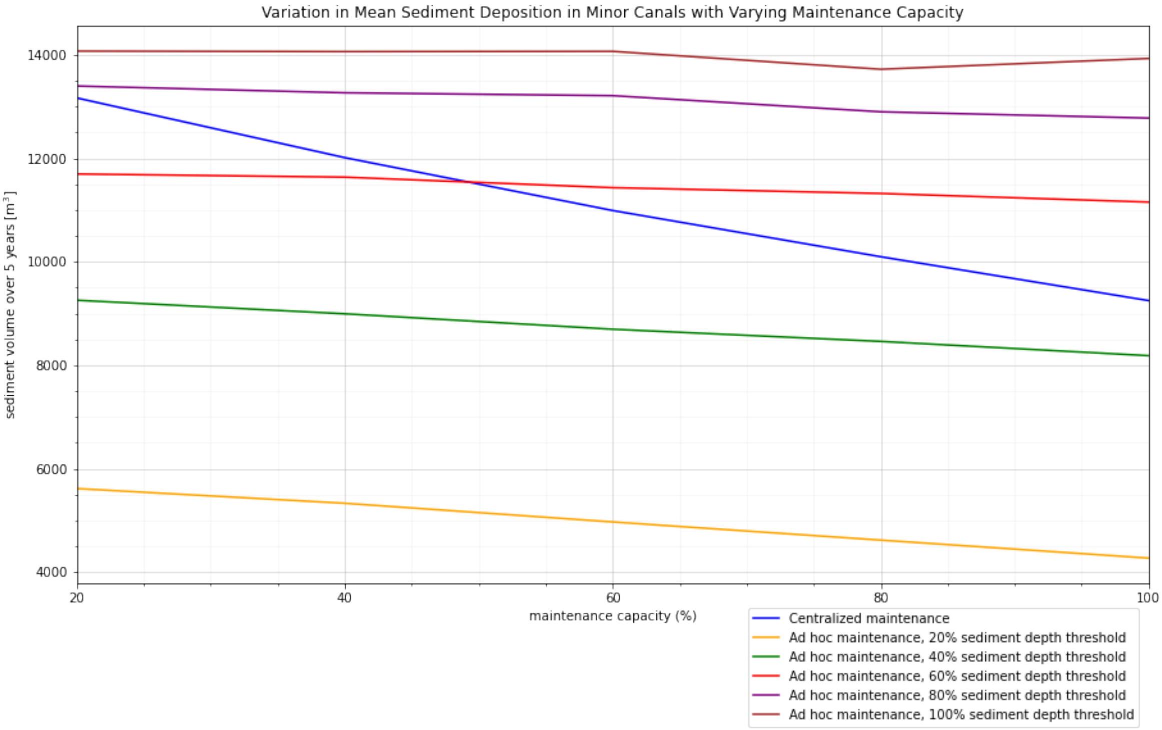


Figure 4.6: Sensitivity of the net sediment deposition with varying maintenance capacity across all minor canals over five years.

As the maintenance capacity increases, the GSAB Model shows a decline in the amount of sediment deposition in the minor canals (Figure 4.6). These results indicate that sediment deposition in the minor canals is highly sensitive to an increase in maintenance capacity, particularly for ad hoc maintenance at low sediment depth thresholds and centralized maintenance (Figure 4.6). This drives the conclusion that for ad hoc maintenance, starting desilting efforts earlier rather than later makes a notable difference in the amount of net sediment deposition in the minor canals.

Centralized Maintenance

The results of the sensitivity analysis show that as the centralized maintenance capacity increases, the total amount of sediment deposition decreases while the amount of desilted sediment increases (Figure 4.7). During the maintenance period when there is no inflow of sediment into the minor canals, the change in the amount of net sediment deposition is less than zero, indicating that sediment removal is occurring in the minor canals (Figure 4.8). Outside of the maintenance period, there is variation in the change in sediment deposition in the minor canals even though the inflow of sediment into the minor canals has restarted (Figure 4.8). This is caused by two features in the GSAB Model:

1. The weir control structures represented by the offtake proportion ($o_{\%}$)
    (a) The model represents the weir control structures at each minor canal offtake by allowing only a proportion of the sediment from the major canal to enter the minor canal (see Section 3.6.2). It only allows sediment to enter the minor canals if there is available space for additional sediment agents; in other words, if the sediment deposition is less than its maximum volume, sediment from the major canal are allowed to enter at an amount equal to the offtake proportion ($o_{\%}$). More available space means that more sediment agents are allowed to enter the minor canal from the major canal, up to the allowable offtake proportion. Larger central maintenance capacities remove larger amounts of sediment, leaving more available space in the minor canals. Therefore, larger central maintenance capacities allow for more sediment to enter the minor canal from the major canal once the maintenance period is over.
2. Resuspension of sediment in the minor canal
    (a) As the sediment agents flow downstream from the offtake to the end of each minor canal, it resuspends sediment based on the erosion flux (see Sections 3.6.1 and 3.6.2). The variation in the accumulated sediment

reflects the resuspension of sediment that are transported and deposited at later time steps depending on the deposition flux and sediment budget.

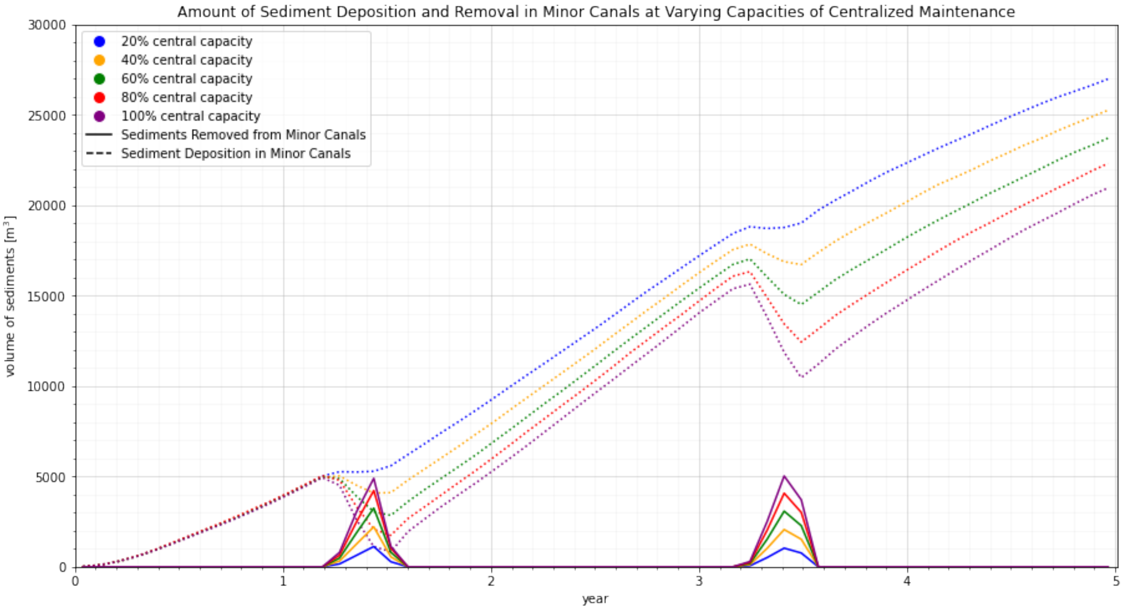


Figure 4.7: Cumulative sediment deposition and removal with varying cap_c.
See Appendix A.1 for isolated graphs by centralized capacity.

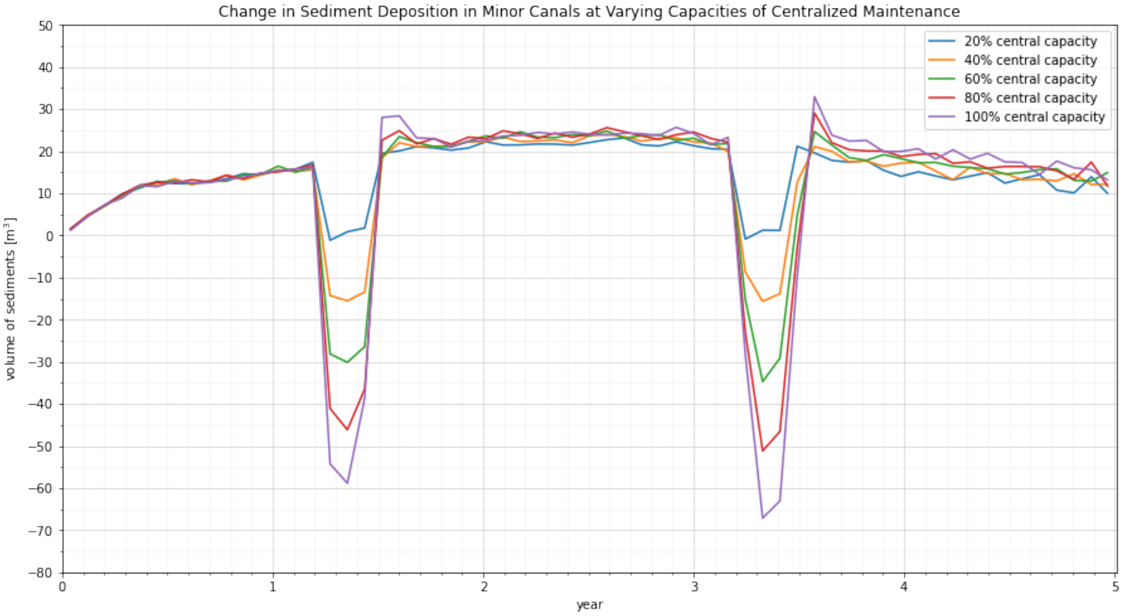


Figure 4.8: Change in net sediment deposition with varying cap_c.
See Appendix A.1 for isolated graphs by centralized capacity. This graph shows the change in the amount of sediment deposition in a given time step. The negative numbers indicate that the net sediment deposition in the minor canals decreased in the year due to maintenance.

Ad hoc Maintenance

During ad hoc maintenance, the canal system remains open; water and sediment continue to flow into the minor canals while the tenants are desilting (see Section 3.3). The results of the sensitivity analysis show that at each value of the ad hoc maintenance capacity, the amount of sediment removal decreases as the the sediment depth threshold ($h_{s,\%}$) increases (Figure 4.9). This indicates lower thresholds ($h_{s,\%}$) allow ad hoc maintenance to start earlier than higher ones, resulting in lower net sediment deposition in the minor canals (Figure 4.6; also see Figures A.11 to A.15). In addition, a higher ad hoc maintenance capacity increases the amount of desilted sediment in the model, leaving less net sediment deposition in the minor canals (Figure 4.9).

In sum, the results of the sensitivity analysis suggest that ad hoc maintenance is most effective when triggered early, specifically before the sediment depth threshold reaches 40% of the maximum depth. If triggered early, ad hoc maintenance leaves less deposited sediment in the minor canals than centralized maintenance, even when only a small proportion of farmers conduct maintenance. On the other hand, centralized maintenance is restricted to the maintenance period, which limits the range of potential sediment removal. Yet, the results of the sensitivity analysis present evidence that centralized maintenance requires a smaller increase in capacity to see bigger improvements in sediment deposition. Additionally, the results indicate that the advantage ad hoc maintenance has over centralized maintenance lies not in its capacity but rather its ability to be triggered early.

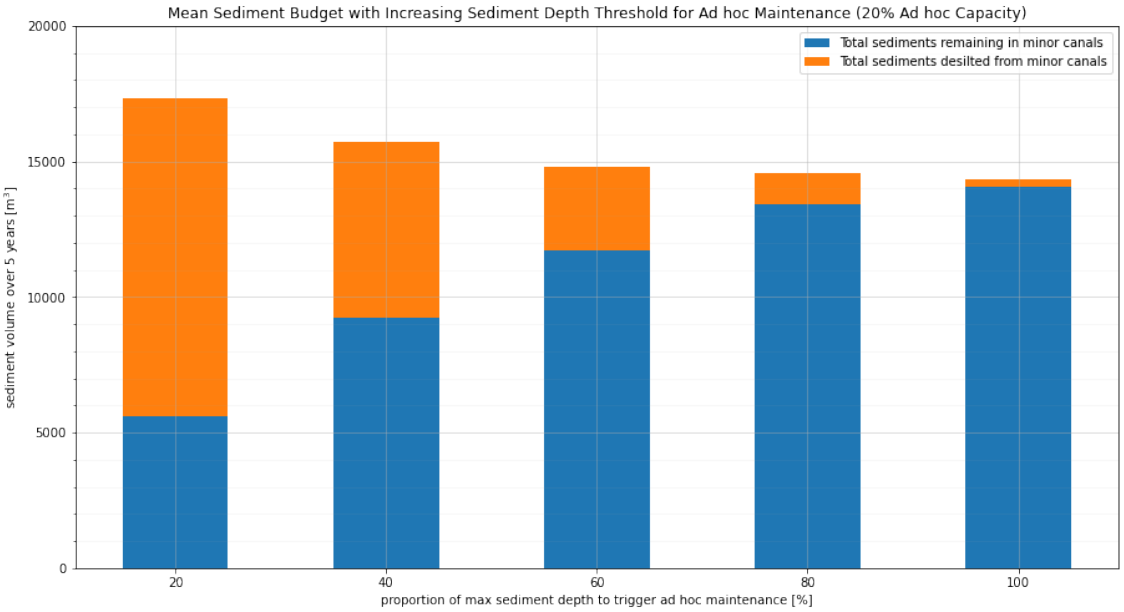


Figure 4.9: Mean sediment deposition and removal with varying $h_{s,\%}$.

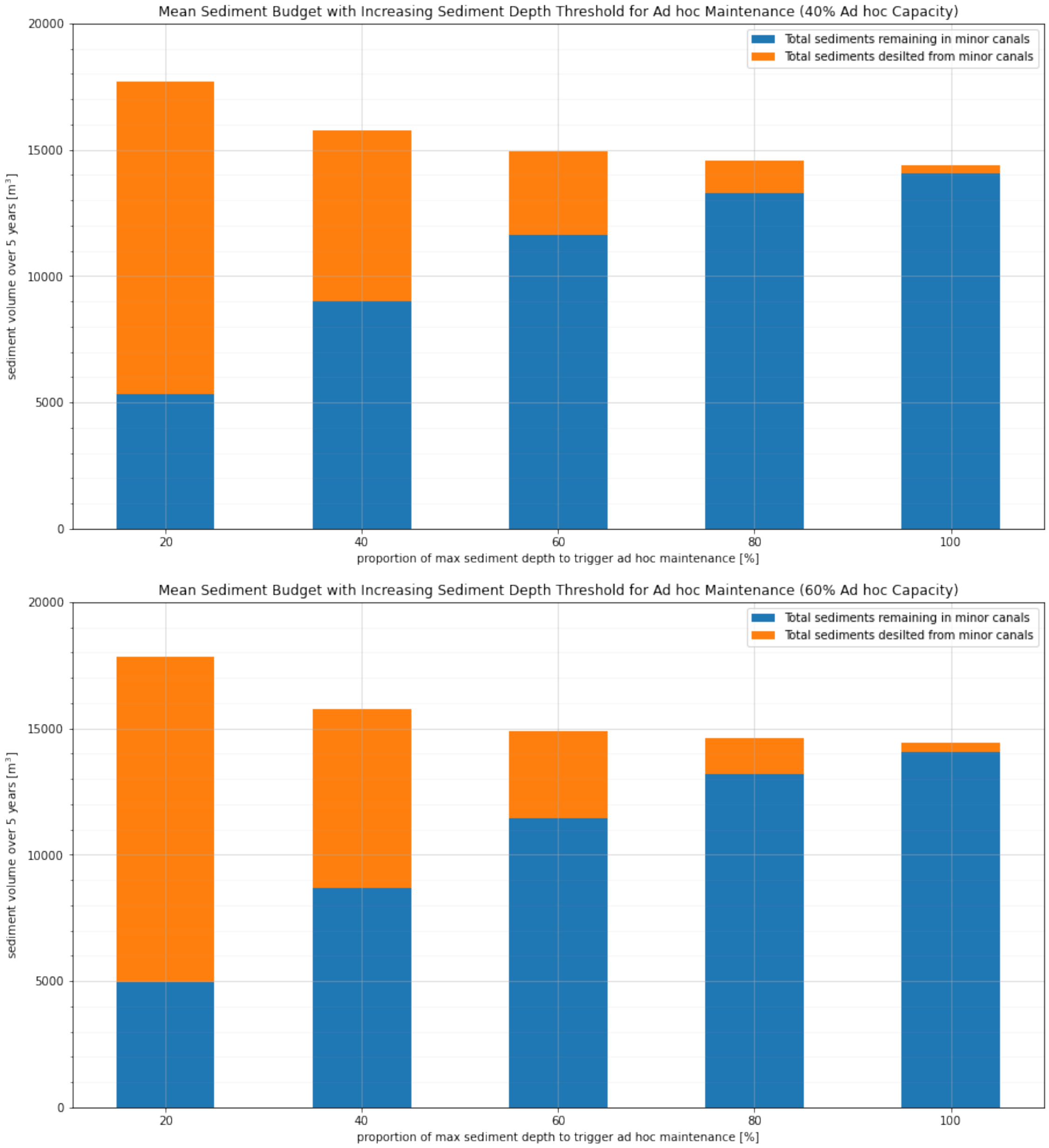


Figure 4.9: Mean sediment deposition and removal with varying $h_{s,\%}$ (continued).

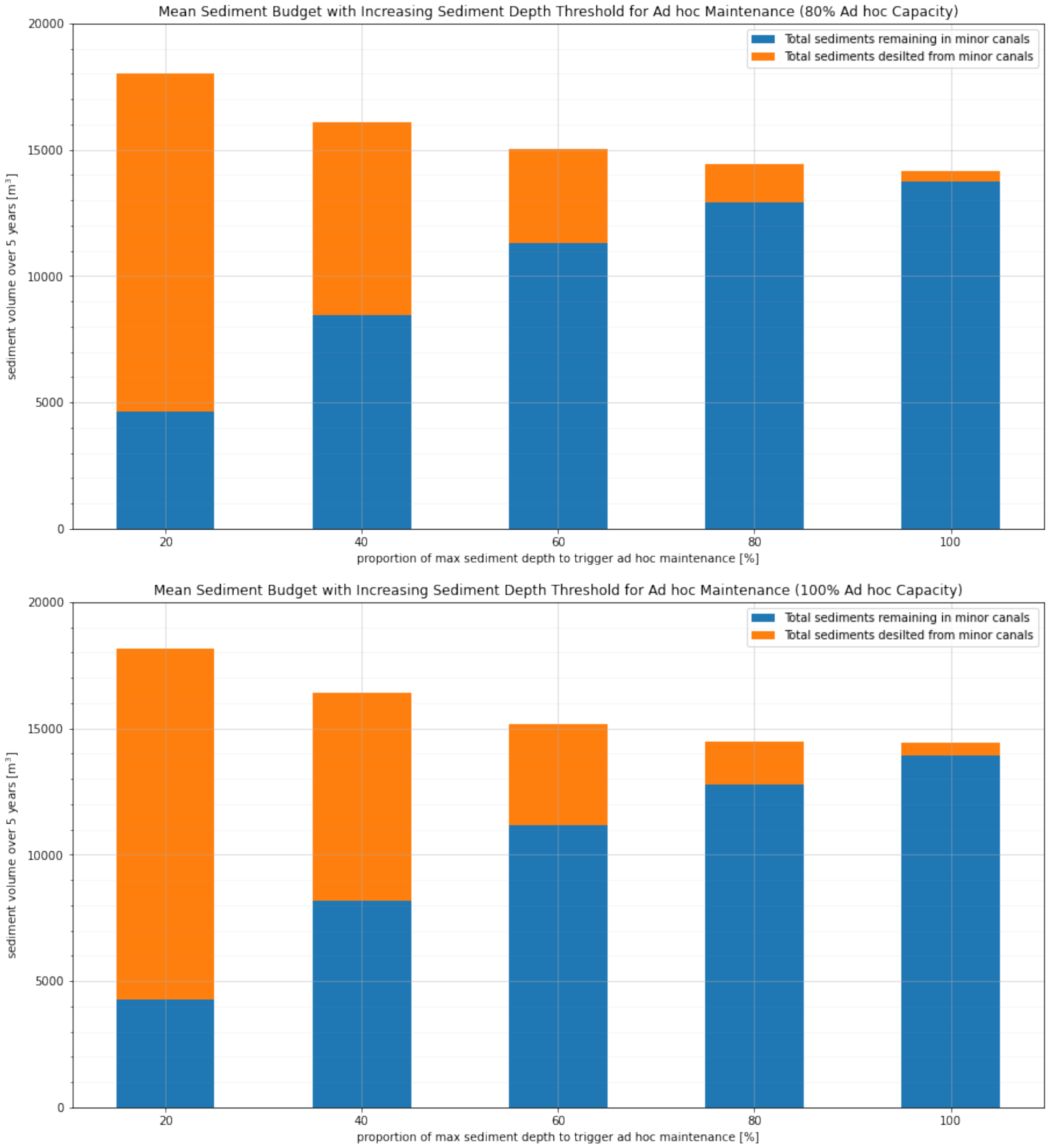


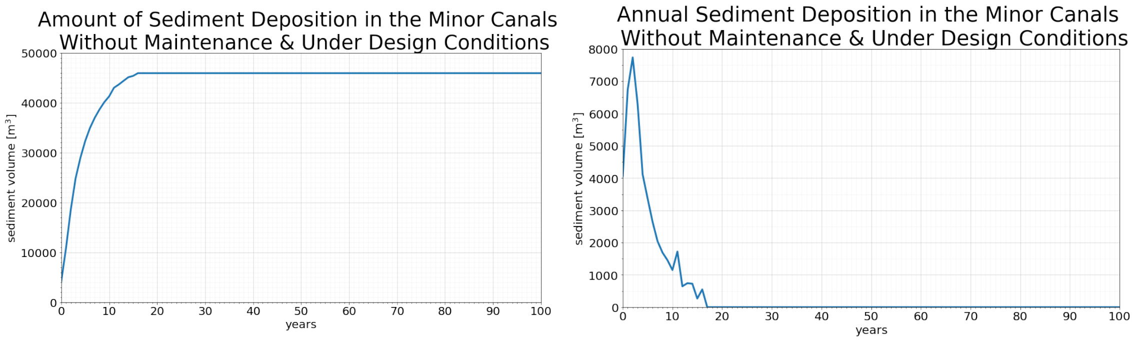
Figure 4.9: Mean sediment deposition and removal with varying $h_{s,\%}$ (continued).

4.2 GSAB Model Results of "No Maintenance" Simulations

"No Maintenance" simulations model sediment deposition in the minor canals under various environmental conditions without maintenance. The GSAB Model regulates the flow of sediment from the major canal into the minor canals based on the amount of sediment already in the minor canal (see Sections 3.3 and 3.6.2). When the minor canals are empty, the portion of sediment agents that are allowed to move from the major canal into the minor canals is determined by the offtake proportion ($o_{\%}$). As the minor canals fill with sediment, the offtake proportion decreases linearly and negatively to the amount of sediment deposited in the minor canals (see Section 3.6.2). Once the minor canals are completely filled with sediment, no additional sediment agents are allowed to enter the minor canals. This simulates the blockage of water and sediment inflow due to sediment accumulation in the minor canals. Because sediment accumulation leaves little space for more water and sediment flow, the GSAB Model stops any additional sediment agents from moving into the minor canals. Only desilting efforts can remove sediment from the minor canals because they do not have drainage; therefore, sediment will stay in the minor canals until maintenance occurs (see Sections 3.3 and 3.6.2). These "no maintenance" simulations provide insight into the sediment deposition rate and the time it takes for the minor canals to accumulate sediment under various conditions.

4.2.1 Design Conditions

Design conditions refer to the situation where the canals operate according to the Lacey regime theory design. This is the default situation where parameters that reflect environmental factors like water flow and sediment concentration are set to the ideal values dictated by Lacey's regime theory design (see Tables 3.1 and 3.5). The parameter values used in this simulation are equal to those used for SIM-1 and SIM-2 in Table 3.5, except for $h_{s,\%}$, cap_c, and cap_a which are set to zero because they is no maintenance.



(a) Amount of sediment deposition over time.

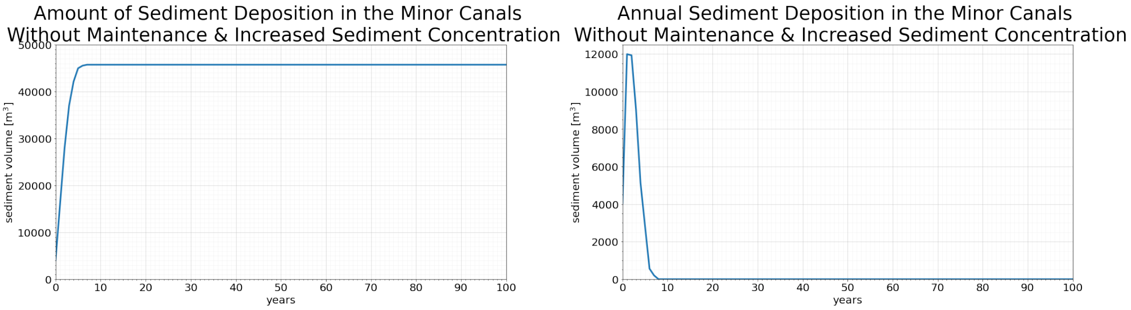
(b) Sediment deposition per year.

Figure 4.10: Sediment deposition with no maintenance and under design conditions (when input parameters are set to the SIM-1 & SIM-2 values denoted in Table 3.5, with the exception of $h_{s,\%}$, cap_c, and cap_a that are all set to zero because there is no maintenance).

The GSAB Model shows that under design conditions and without maintenance, it takes 16 years for all the minor canals to be completely filled with sediment; in that time, the average sediment deposition per year is 2,702 m^3 (Figure 4.10). Due to the conceptualization of the GSAB Model, sediment agents are not allowed to enter the minor canals from the major canal once the minor canals are full. After 16 years, there is no additional sediment deposition as the amount of sediment accumulation in the minor canals has reached the maximum minor canal volume (see Section 3.6.2). Figure 4.10a shows that the amount of sediment deposition in the minor canals increases until year 17 when it plateaus because the maximum volume of the minor canals is reached. Figure 4.10b shows that after starting the simulation, the annual sediment deposition rate decreases as the minor canals are filling and additional sediment agents are barred from entering the minor canals; after 16 years, the sediment deposition rate becomes zero as the minor canals in the GSAB Model are completely filled with sediment. Since there is no maintenance, the sediment remain the minor canals until the end of the simulation.

4.2.2 Increased Sediment Concentration

In this simulation, the parameter values for SIM-3, SIM-4, and SIM-4.5 in Table 3.5 are used, with the exception of $h_{s,\%}$, cap_c, and cap_a which are set to zero to represent no maintenance.



(a) Amount of sediment deposition over time.

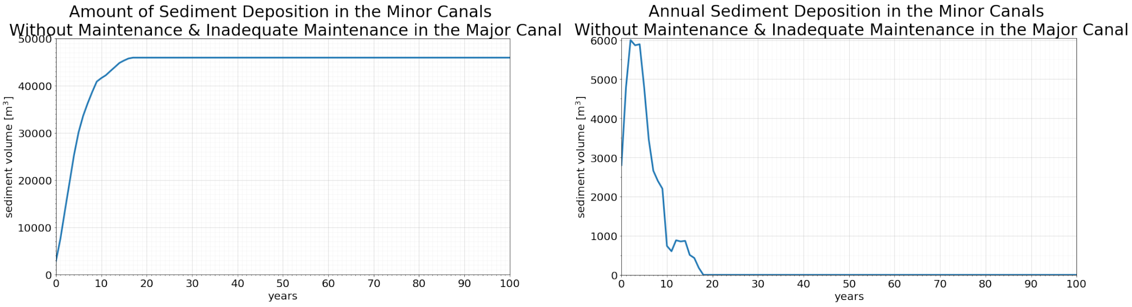
(b) Sediment deposition per year.

Figure 4.11: Sediment deposition with no maintenance & increased sediment concentration (when input parameters are set to the SIM-3, SIM-4 & SIM-4.5 values denoted in Table 3.5, with the exception of $h_{s,\%}$, cap_c, and cap_a that are all set to zero because there is no maintenance).

The GSAB Model suggests that with an increase in sediment concentration to 10,000 ppm, it takes seven years for the minor canals to be completely filled with sediment; in that time, the average annual sediment deposition is 5,741 m^3 (Figure 4.11). In the model, a higher sediment concentration increases the sediment deposition rate which causes the minor canals to be filled much quicker than under design conditions. Once the upper boundary of the maximum volume of the minor canals is reached, the GSAB Model stops the inflow of additional sediment agents from the major canal. This simulates the blockage of water flow due to sediment accumulation (see Sections 3.3 and 3.6.2). The higher sediment load causes the maximum volume of the minor canals to be reached much faster than under design conditions. This is shown by the rapid increase in the amount of sediment deposition in the minor canals after starting the simulation (Figure 4.11a). In addition, the annual sediment deposition rate is high at the beginning of the simulation; it quickly decreases until it becomes zero after seven years because the higher sediment load causes the minor canals to accumulate sediment quickly (Figure 4.11b). The increase in sediment concentration to 10,000 ppm represents erosion in the upstream areas (see Section 3.5.1); the results of this simulation drive the conclusion that upstream erosion leads to more sediment deposition in the minor canals.

4.2.3 Inadequate Maintenance in the Zananda Major Canal

When there is inadequate maintenance in the Zananda Major Canal, sediment accumulates in the major canal and disrupts the water flow. The disruption of flow in the major canal leads to less water flowing into the minor canals from the major canal. Less water inflow means that less sediment is entering the minor canals, as sediment are transported in suspension (see Section 2.1.2). In this simulation, the parameters are set to the values of SIM-5 and SIM-6 in Table 3.5, with the exception of $h_{s,\%}$, cap_c, and cap_a which are set to zero to represent no maintenance.



(a) Amount of sediment deposition over time.

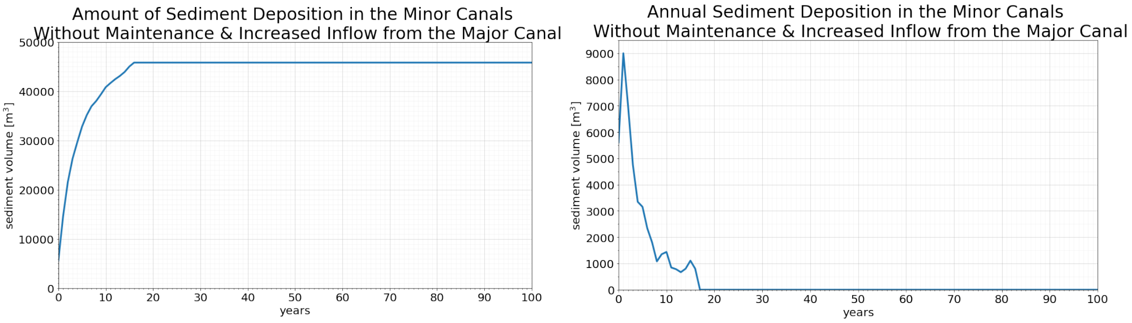
(b) Sediment deposition per year.

Figure 4.12: Sediment deposition with no maintenance & inadequate maintenance in the major canal (when input parameters are set to the SIM-5 & SIM-6 values denoted in Table 3.5, with the exception of $h_{s,\%}$, cap_c, and cap_a that are all set to zero because there is no maintenance).

The GSAB Model shows that it takes 18 years for the minor canals to be completely filled with sediment; in that time, the average annual sediment deposition rate is 2,551 m^3 (Figure 4.12). Again, the amount of sediment deposition in the minor canals increases until it plateaus after 18 years because the minor canals are completely filled in the model world (Figure 4.12a). The annual sediment deposition rate decreases after the start of the simulation until the 18th year; as the minor canals are filling with sediment, the annual sediment deposition rate decreases as there is increasingly less available space (Figure 4.12b).

4.2.4 Increased Inflow from the Zananda Major Canal

In this simulation, the parameter values for SIM-7 and SIM-8 in Table 3.5 are used, with the exception of $h_{s,\%}$, cap_c, and cap_a which are set to zero to represent no maintenance.


Amount of Sediment Deposition in the Minor Canals Without Maintenance & Increased Inflow from the Major Canal

Annual Sediment Deposition in the Minor Canals Without Maintenance & Increased Inflow from the Major Canal

(a) Amount of sediment deposition over time.

(b) Sediment deposition per year.

Figure 4.13: Sediment deposition with no maintenance & increased inflow from the major canal (when input parameters are set to the SIM-7 & SIM-8 values denoted in Table 3.5, with the exception of $h_{s,\%}$, cap_c, and cap_a that are all set to zero because there is no maintenance).

The results of this simulation suggest that with a higher inflow of water and sediment from the Zananda Major Canal, it takes 16 years for the minor canals to be completely filled with sediment; in this time, the average annual sediment deposition is 2,695 m^3 (Figure 4.13). Interestingly, this outcome is comparable to the results of the "no maintenance" simulation under design conditions (Section 4.2.1). This could be caused by the small width of the offtakes at only three patches wide in the model world. Sediment agents on the major canal have to move to the offtakes' patches before they can consider moving into the minor canal patches. The small size of the offtakes in the GSAB Model could be limiting the number of sediment agents that are able to move onto the offtakes' patches; even if the offtake proportion (the likelihood that they will move into the minor canals) increases, a bottleneck occurs at the offtakes. Yet, the annual sediment deposition rate in the first year is much higher with an increased inflow than under design conditions; this is shown by the higher peak in the first year of Figure 4.13b compared to that of Figure 4.10b. This implies that the higher inflow of sediment agents causes a higher sediment deposition at the outset; as the minor canals fill with sediment, the annual sediment deposition rate decreases until the minor canals are completely filled.

This situation represents the effect of an increase in water flow due to the construction of the Manaqil Extension in the 1960s and higher water demand from more crop production. The results of this simulation with an increased inflow present evidence that a higher water discharge in the main canals may not trickle down to the minor canals; in addition, the weir control structures may be sufficient for controlling the water and sediment inflow into the minor canals.

In sum, Figures 4.10, 4.11, 4.12, and 4.13 show that without maintenance, the minor canals in the GSAB Model become fully filled with sediment within two decades regardless of environmental conditions and maintenance in the major canal. Maintenance is required to remove sediment from the minor canals, as there is no drainage from the minor canals (see Section 3.6.3). Table 4.3 summarizes the results of running simulations without maintenance under design conditions, increased sediment concentration, inadequate maintenance in the major canal, and increased inflow from the major canal. These results indicate that an increased sediment concentration causes the highest sediment deposition rate, even more so than a higher water discharge into the minor canals.

Scenario without Maintenance	Time until Minor Canals are Filled [years]	Average Sediment Deposition Per Year before Minor Canals are Filled [m^3]
Design Conditions (SIM-1 & 2 parameters, except without maintenance)	16	2,702
Increased Sediment Concentration (SIM-3, 4 & 4.5 parameters, except without maintenance)	7	5,741
Inadequate Maintenance in the Major Canal (SIM-5 & 6 parameters, except without maintenance)	18	2,551
Additional Inflow from the Major Canal (SIM-7 & 8 parameters, except without maintenance)	16	2,695

Table 4.3: Average sediment deposition in minor canals with no maintenance under various environmental and maintenance conditions.

Chapter 5

Results: Gezira Sedimentation Agent-based (GSAB) Model Scenarios

5.1 Results of SIM-1: Centralized Reference Scenario

As mentioned in Section 3.8, the flow of sediment agents into and out of the Zananda Major Canal is stable in SIM-1; the number of sediment agents in the major canal remains consistent throughout the simulation (Figures 5.1 and 5.2). The variation in the outflow of sediment agents is caused by the centralized maintenance period every two years, during which the movement of sediment from the major canal into the minor canals is halted for three months (see Sections 3.3 and 3.6.3). In the years when centralized maintenance occurs, sediment agents leave the major canal only through drainage at the end of the major canal (K16.7 in Figure 3.2). On average, there are 1,439 sediment agents in the Zananda Major Canal throughout the 100-year simulation. The sediment deposition in the Zananda Major Canal is 5,417 m^3 per year on average (Figure 5.2).

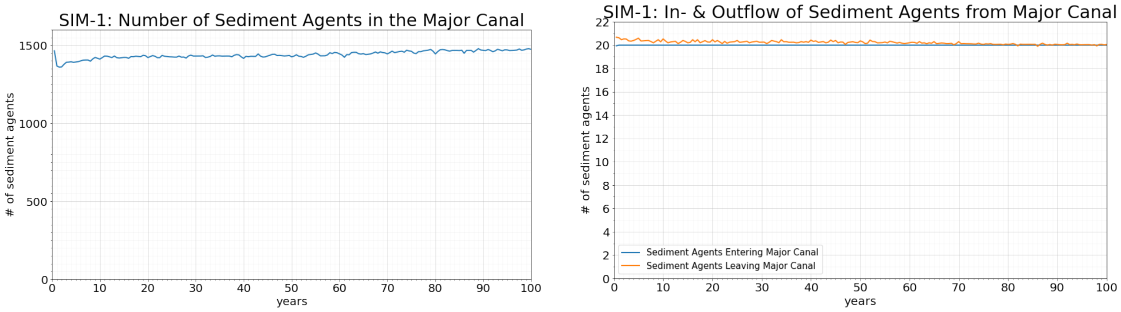


Figure 5.1: SIM-1: Sediment agents in the Zananda Major Canal.

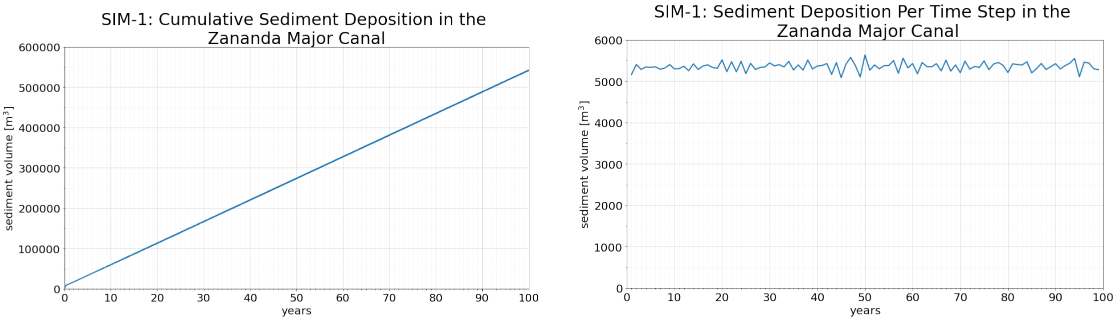


Figure 5.2: SIM-1: Sediment deposition in the Zananda Major Canal.

At the end of the 100-year simulation, the net sediment deposition in the minor canals is 31,896 m^3; the average net sediment deposition with centralized maintenance under design conditions is 306 m^3 per year in the minor canals (Figure 5.3). The blue line in Figure 5.3 shows the net sediment deposition in the minor canals after maintenance occurs; it is the amount of sediment deposition in the minor canals at any given time step. The first 10 years of the simulation is the model's "warm-up" period where the model stabilizing. This period represents the time it takes for the minor canals to be filled with sediment; at the start of the simulation, the minor canal patches have no sediment agents on them (Figure 5.3). This represents that upon completion of the Gezira Scheme in the 1920s, the minor canals were empty; it took time for them to be filled with water and sediment flowing in from the major canal. However, in the GSAB Model, the sediment transport and deposition are represented by sediment agents, not water agents. Each sediment agent carries a certain amount of sediment which is scaled and calibrated to real-world magnitudes to avoid having to create a large number of sediment agents that Netlogo cannot accommodate (see Sections 3.6 and 3.7). The sediment agents can only move downstream one patch at a time in each time step representing one day. In reality, water and sediment would reach the end of the minor canal within the first year. However, the GSAB Model has a one-decade warm-up period while the sediment agents move down the minor canal according to how the GSAB Model was conceptualized.

The average sediment removal over the 100-year simulation is 1,947 m^3 per year (Figure 5.3). The orange line in Figure 5.3 shows the amount of sediment removed by centralized maintenance in any given time step. The amount of sediment removal correlates with the decrease in net sediment deposition that occurs every two years during centralized maintenance; the biennial schedule of centralized maintenance causes the "zigzag" in the graph because during the years where no maintenance occurs, the sediment removal is zero (Figure 5.3). After the model's warm-up period, the amount of sediment removed every two years is around 4,000 m^3 (Figure 5.3).

With this amount of sediment removal, 69% of the minor canals' maximum volume is filled with sediment at the end of the 100-year simulation.

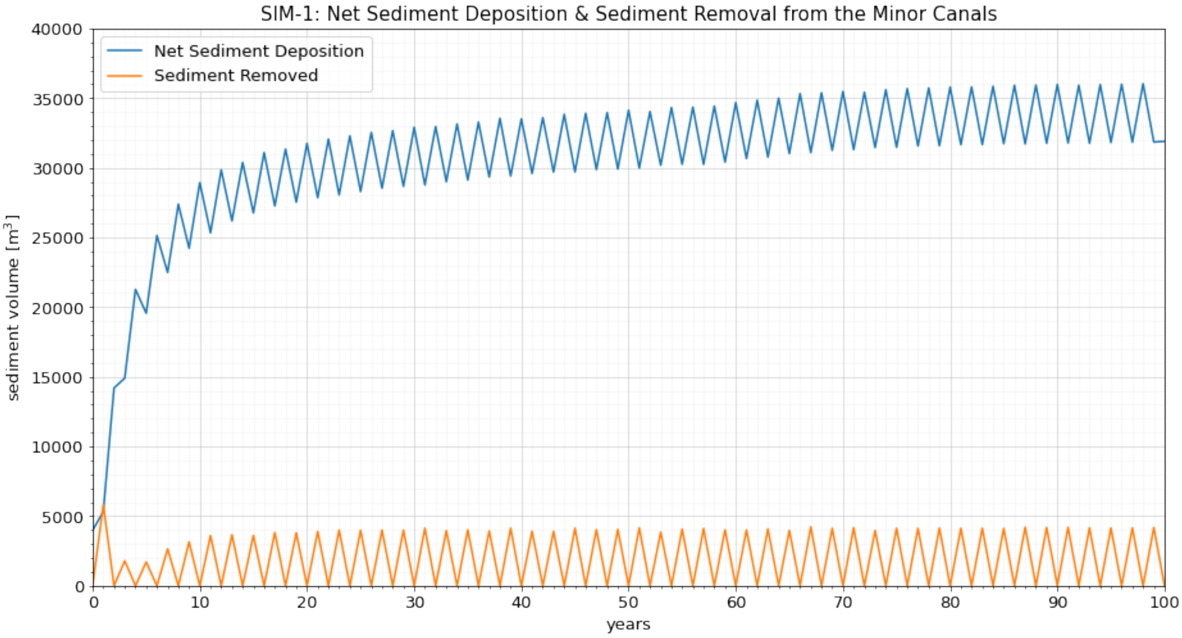


Figure 5.3: SIM-1: Net sediment deposition & removal of the minor canals.

The results of SIM-1 suggest that even before Sudan's independence in the 1950s (see Figure 2.2), centralized maintenance did not fully remove all deposited sediment in the minor canals. Yet, centralized maintenance is able to remove enough sediment so that over time, the net sediment deposition stabilizes. The outcome of SIM-1 implies that centralized maintenance can maintain a steady level of sediment removal so that the sediment deposition in the minor canals is mitigated.

5.2 Results of SIM-2: Ad hoc Maintenance Scenario

Similar to SIM-1 (Section 5.1), the flow sediment agents into and out of the Zananda Major Canal is stable (Figures 5.4 and 5.5). However, with ad hoc maintenance, there is continual flow of sediment agents from the Zananda Major Canal into the minor canals in the model world. Earlier on in the simulation when the minor canals are still empty, there is slightly more sediment agents leaving the major canal as the full offtake proportion is allowed to flow into the minor canals. As the minor canals fill with sediment, sediment agents from the major canal start to become increasingly restricted from flowing into the minor canals. Like SIM-1, there are 1,439 sediment agents on average in the Zananda Major Canal throughout the 100-year simulation, and the average annual sediment deposition is 5,417 m^3. This confirms that between SIM-1 and SIM-2, the flow of sediment agents and deposition in the Zananda Major Canal are similar in the GSAB Model.

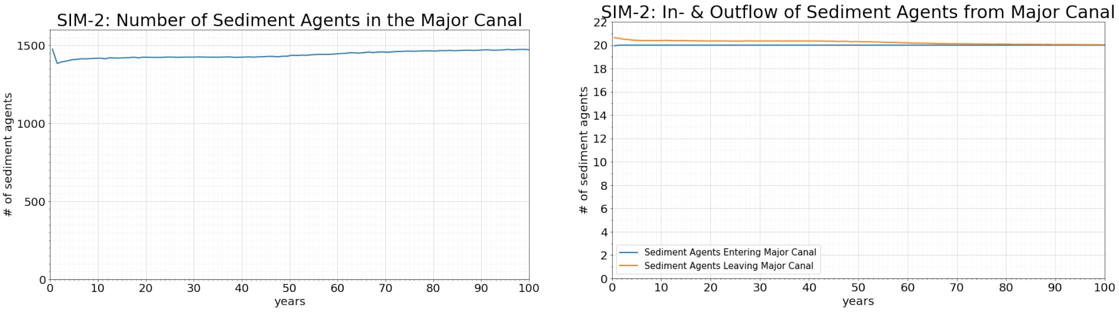


Figure 5.4: SIM-2: Sediment agents in the Zananda Major Canal.

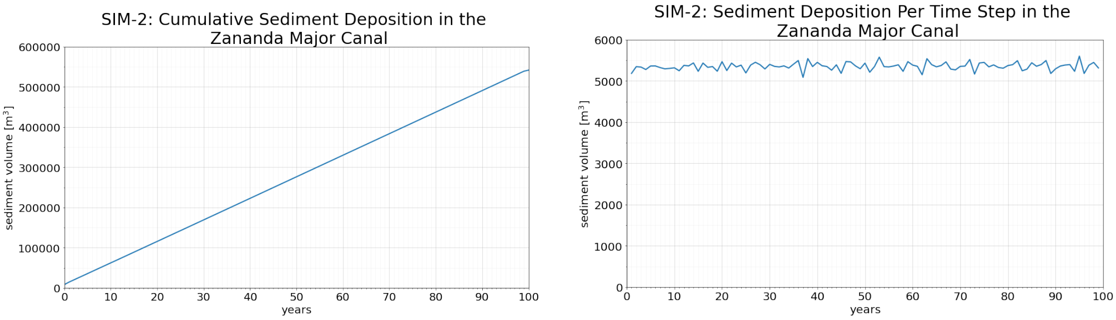


Figure 5.5: SIM-2: Sediment deposition in the Zananda Major Canal.

At the end of the 100-year simulation, the net sediment deposition in the minor canals is 30,702 m^3 (Figure 5.6), approximately 4% less than that of SIM-1. This represents approximately 67% of the minor canals filled with sediment at the end of the 100-year simulation and an average annual net sediment deposition of 275 m^3. Like SIM-1, the model has a warm-up period where the sediment agents are filling the minor canals after the start of the simulation. The smoother lines in Figure 5.6 compared to the blue line for SIM-1 in Figure 5.3 reflects the nature of ad hoc maintenance; it can occur at any time throughout the year and in any given year as long as the sediment depth threshold ($h_{s,\%}$) is reached. As shown by the orange line in Figure 5.6, the amount of sediment removal stays relatively constant throughout the simulation after the warm-up period, unlike in centralized maintenance that occurs only every two years.

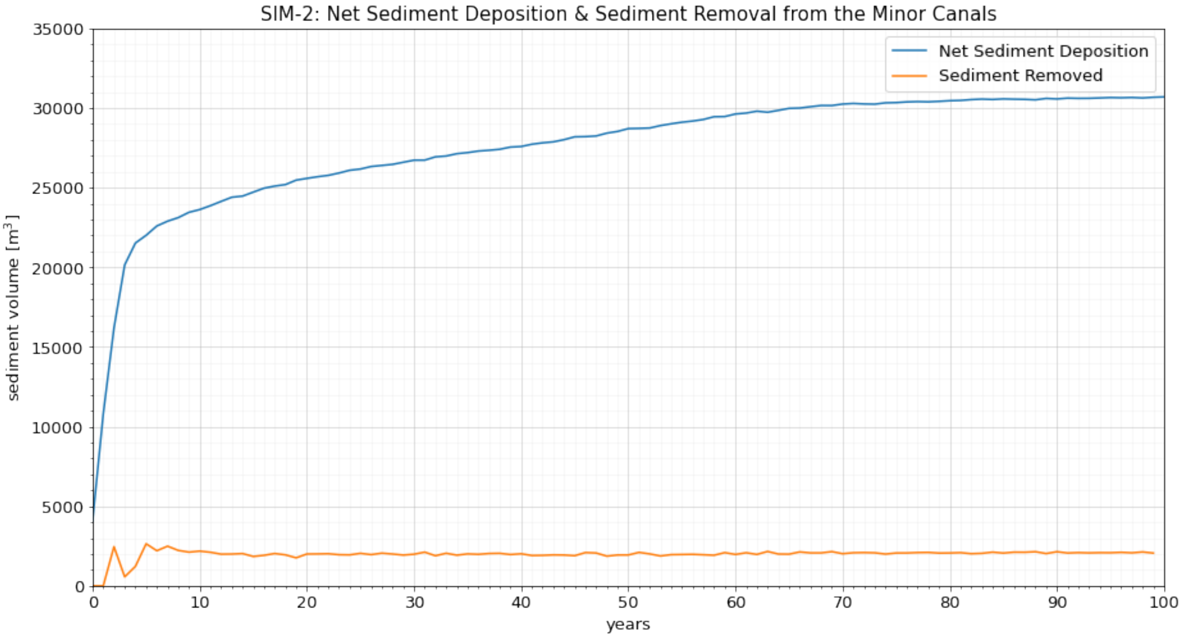


Figure 5.6: SIM-2: Net sediment deposition & removal of the minor canals.

On average, the annual sediment removal is higher in SIM-2 than SIM-1 at 1,978 m^3 per year (Figure 5.7). The results of SIM-2 indicate that there is less net sediment deposition in the minor canals after 100 years with ad hoc maintenance compared to centralized maintenance. This is the case even though the canal system remains open throughout the year during ad hoc maintenance, while the canal system is closed during the maintenance period every two years during centralized maintenance. The outcome of this scenario suggests that the higher sediment removal rate allows ad hoc maintenance to make up for the fact that the canal system is open all year round. With a sediment depth threshold ($h_{s,\%}$) of 70% under design conditions, ad hoc maintenance begins on day 58 of the third year (day 788) in the GSAB Model and occurs every year after that (Figure 5.7).

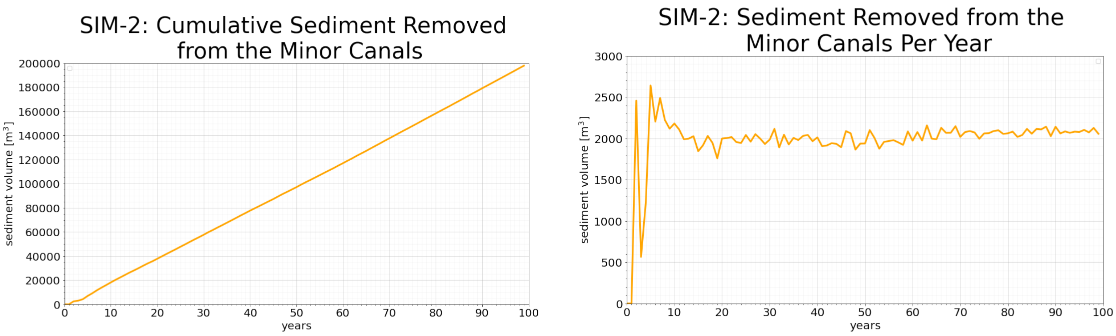


Figure 5.7: SIM-2: Sediment removal from the minor canals over time.

The results of SIM-2 present evidence that tenant-run ad hoc maintenance mitigates sediment deposition in the minor canals more effectively than centralized maintenance. While ad hoc maintenance still does not fully remove all sediment from the minor canals, its consistency results in a lower level of net sediment deposition and less fluctuation from year to year in the GSAB Model.

5.3 Results of SIM-3: Increased Sediment Concentration with Centralized Maintenance

The flow of sediment agents into and out of the Zananda Major Canal in SIM-3 is comparable to that of SIM-1 and SIM-2 (Figure 5.8). However, with the sediment concentration increasing from 6,000 ppm in SIM-1 and SIM-2 to 10,000 ppm in SIM-3, the sediment deposition in the Zananda Major Canal increases by approximately 150%; the average annual sediment deposition rises to 13,593 m^3 (Figure 5.9). On average, there are 1,454 sediment agents in the Zananda Major Canal throughout the 100-year simulation. This higher number of sediment agents compared to SIM-1 and SIM-2 indicates that as the minor canals fill with sediment more quickly due to the higher sediment concentration, additional sediment agents are not allowed to move from the major canal into the minor canals; therefore, they remain in the major canal.

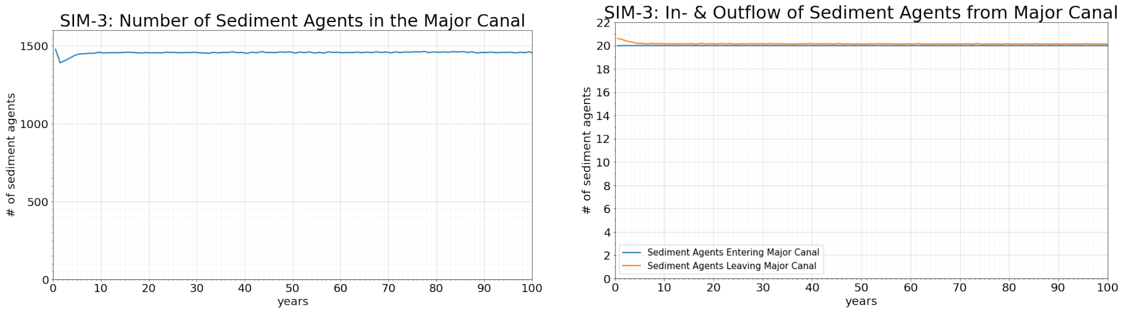


Figure 5.8: SIM-3: Sediment agents in the Zananda Major Canal.

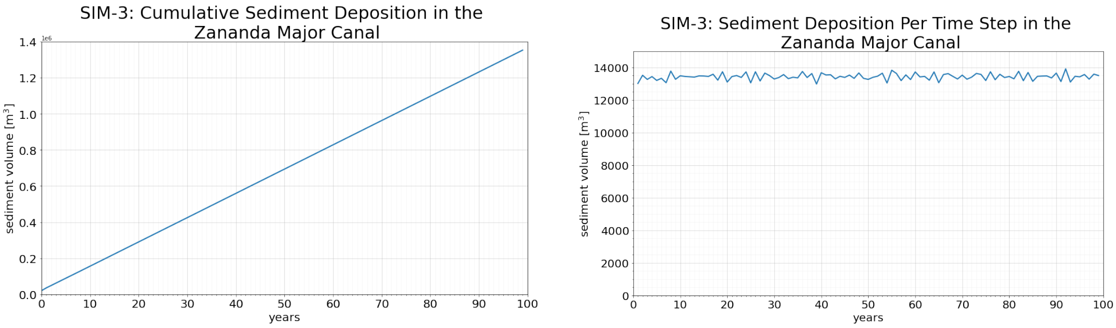


Figure 5.9: SIM-3: Sediment deposition in the Zananda Major Canal.

At the end of the 100-year simulation, the net sediment deposition in the minor canals is 39,351 m^3, approximately 86% of the total volume of the minor canals in the GSAB Model (Figure 5.10). The average net sediment deposition per year is 400 m^3. The results of SIM-3 indicate that a higher sediment concentration leads to more sediment deposition in the minor canals because it increases the deposition flux. There is a shorter warm-up, stabilization period of about five years compared to that of SIM-1 because the higher sediment concentration fills the minor canals faster in SIM-3 than SIM-1. Once the upper boundary of the maximum volume of the minor canal is reached, the GSAB Model restricts additional sediment agents from entering the minor canal. This simulates the blockage of water flow from the major canal due to sediment accumulation, as there is increasingly less available space in the minor canal for additional water and sediment flow (see Sections 3.3 and 3.6.2). The GSAB Model prevents the sediment deposition in the minor canals from exceeding the maximum volume; this is why in this scenario, the amount of sediment deposition rises quickly until it reaches the upper boundary; then, it plateaus. The only way to remove the sediments in the minor canals is by performing maintenance (see Section 3.6.3).

On average, centralized maintenance removes 1,931 m^3 of sediment per year in this scenario. This is slightly less than the annual average sediment removal of SIM-1. While the maintenance capacity between SIM-1 and SIM-3 did not change, this slight decrease in the average sediment removal could be an artefact of the Netlogo model. There is some randomness in the model due to the offtake proportion (see Section 3.4). Yet, even with an additional 16 m^3 of sediment removal per year to match the sediment removal rate of SIM-1[1], the net sediment sediment deposition in the minor canals would still be 38,351 m^3 after the 100-year simulation[2]. This is still 20% greater than the net sediment deposition of SIM-1 after 100 years.

---

[1] The average sediment removal rate of SIM-1 at 1,947 m^3 per year minus the average sediment removal rate of SIM-3 at 1,931 m^3 per year

[2] 39,351 m^3 − (16 m^3 × 100 years)

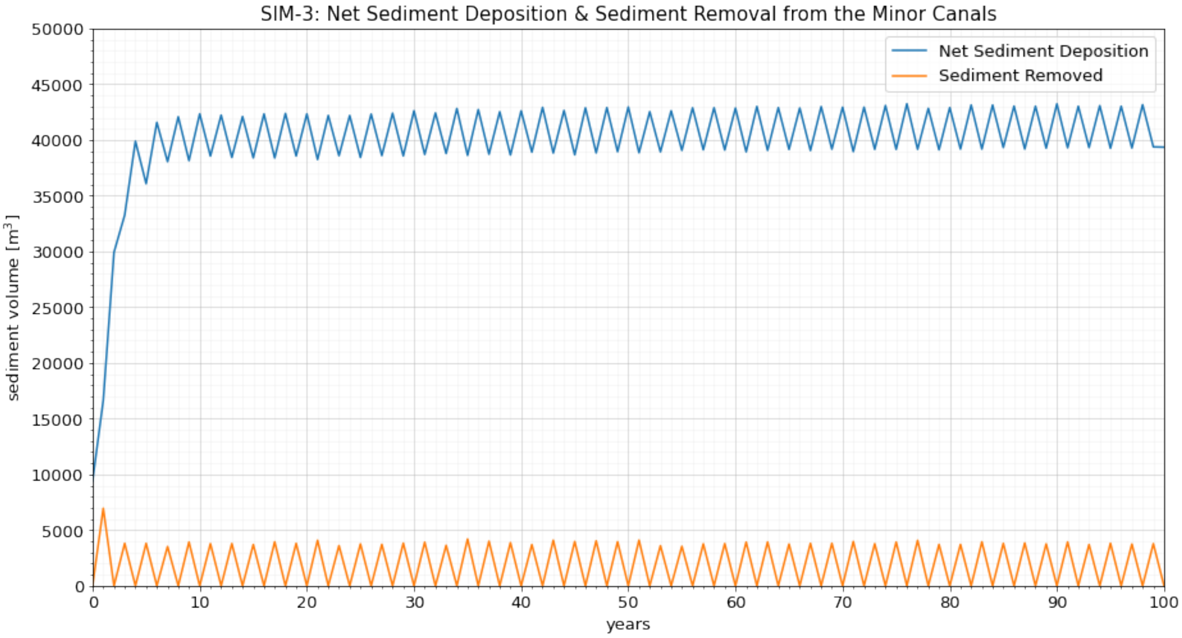


Figure 5.10: SIM-3: Net sediment deposition & removal of the minor canals.

The results of SIM-3 support the conclusion that a higher sediment concentration fills the minor canals with sediment much quicker than under normal environmental conditions. This suggests that a high sediment load causes the minor canals to be clogged with sediment much quicker, leading to a restriction of water and sediment inflow from the major canal. While centralized maintenance mitigates the net sediment deposition in the minor canals, it does not effectively unclog the minor canals. The clogging of the minor canals results in the high net sediment deposition found in this scenario.

5.4 Results of SIM-4: Increased Sediment Concentration with Ad hoc Maintenance

The flow of sediment agents into and out of the Zananda Major Canal is stable in SIM-4 and comparable to that of SIM-3 due to the increased sediment concentration (Figures 5.11 and 5.12). Like SIM-1 and SIM-2, there are 1,439 sediment agents on average in the Zananda Major Canal throughout the 100-year simulation. This implies that ad hoc maintenance is effective at removing sediment from the minor canals, allowing sediment agents from the major canal to enter the minor canals and leaving a similar number of agents in the major canal as under design conditions. Yet, because of the high sediment concentration, the average annual sediment deposition in the major canal is 13,594 m^3, comparable to that of SIM-3 (Figure 5.12).

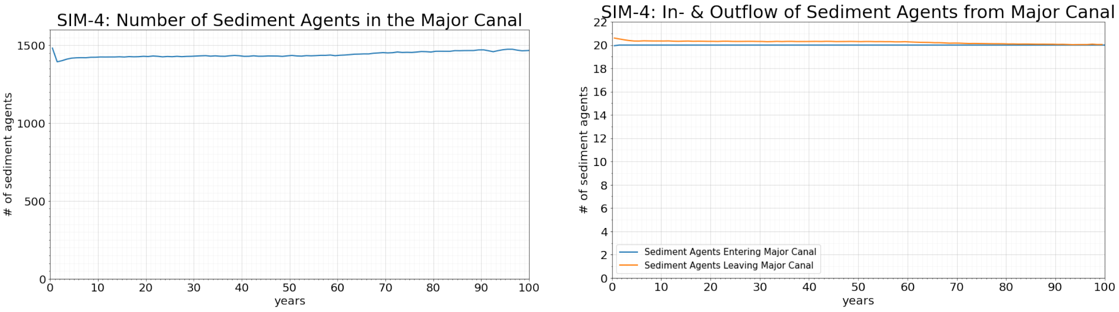


Figure 5.11: SIM-4: Sediment agents in the Zananda Major Canal.

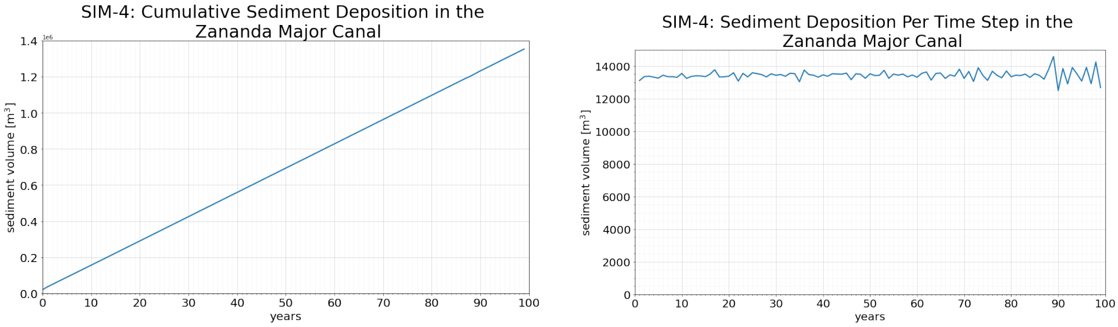


Figure 5.12: SIM-4: Sediment deposition in the Zananda Major Canal.

The net sediment deposition after 100 years and average annual net sediment deposition in the minor canals is 30,673 m^3 and 291 m^3, respectively, which is comparable to those of SIM-2 (Figure 5.13). Yet, the average sediment removal per year from the minor canals is 2,037 m^3, an increase of 59 m^3 per year from SIM-2 (Figure 5.14). This suggests that ad hoc maintenance is adaptable; despite the 67% increase in sediment concentration, ad hoc maintenance has sufficient capacity to desilt enough sediment so that the net sediment deposition after 100 years is comparable to the scenario under design conditions. The adaptability of ad hoc maintenance is demonstrated by an earlier start to ad hoc maintenance on day 297 in SIM-4 rather than day 788 in SIM-2; ad hoc maintenance can begin as soon as the sediment depth reaches the threshold ($h_{s,\%}$; see Section 3.6.3). This therefore suggests that the longer duration of ad hoc maintenance allows for more sediment to be desilted over time.

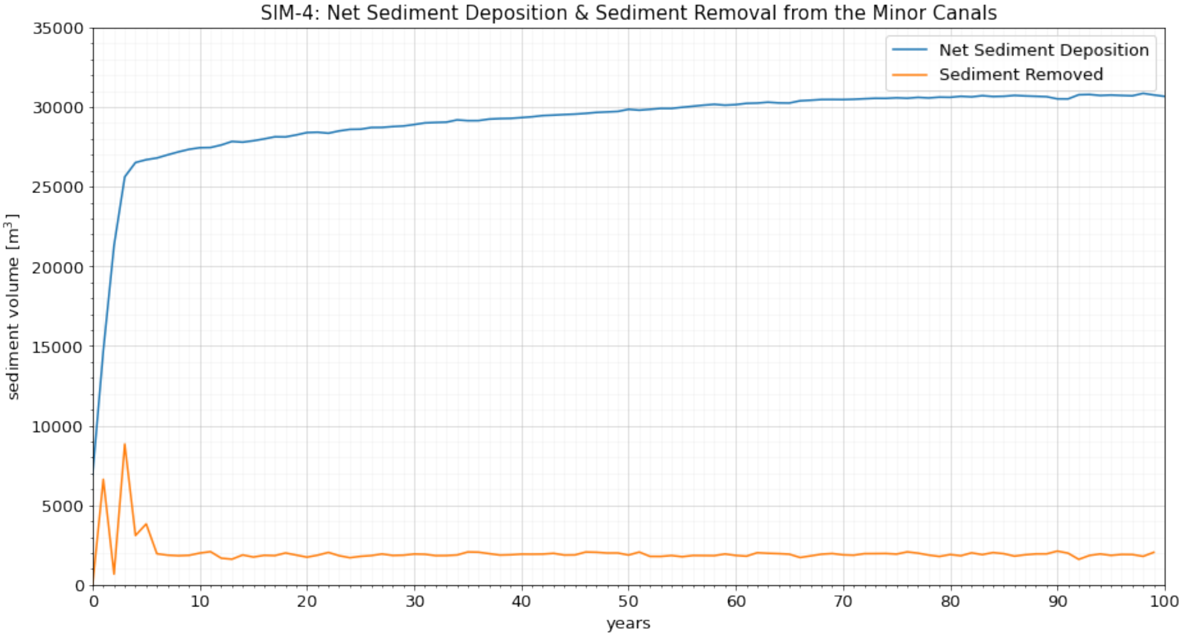


Figure 5.13: SIM-4: Net sediment deposition & removal of the minor canals.

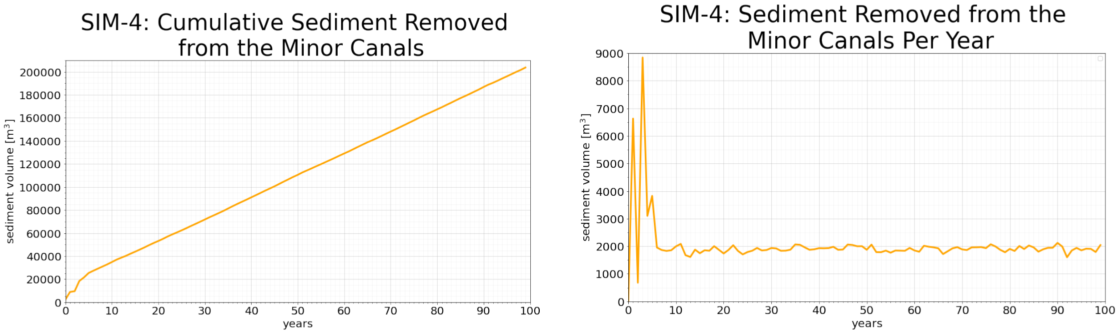


Figure 5.14: SIM-4: Sediment removal from the minor canals over time.

Like in SIM-3, the sediment concentration in SIM-4 is increased to 10,000 ppm, causing the minor canals to accumulate sediment more quickly than under design conditions. However, the results of SIM-4 provides evidence that ad hoc maintenance has the capacity to unclog the minor canals so that the net sediment deposition is comparable to those under design conditions.

5.5 Results of SIM-4.5: Increased Sediment Concentration with Ad hoc Maintenance Capacity at 50%

The flow of sediment agents into and out of the Zananda Major Canal is stable in SIM-4.5 and comparable to that of SIM-3 and SIM-4 due to the increase in sediment concentration (Figures 5.15 and 5.16). Like SIM-1, SIM-2, and SIM-4, there are 1,439 sediment agents on average in the Zananda Major Canal throughout the 100-year simulation. On average, the sediment deposition in the major canal is 13,590 m^3 per year, comparable to those of SIM-3 and SIM-4. This is expected as the higher sediment concentration leads to a higher sediment deposition rate even in the major canal.

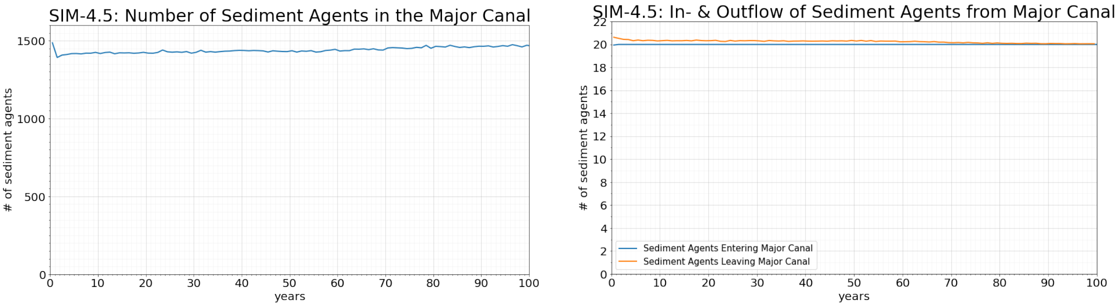


Figure 5.15: SIM-4.5: Sediment agents in the Zananda Major Canal.

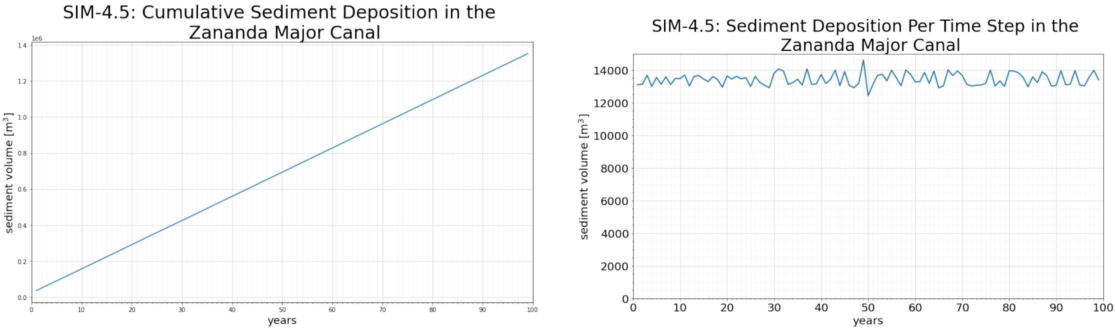


Figure 5.16: SIM-4.5: Sediment deposition in the Zananda Major Canal.

The net sediment deposition after 100 years and average annual net sediment deposition in the minor canals is 31,336 m^3 and 296 m^3, respectively, which is comparable to those of SIM-1 despite the decrease in ad hoc maintenance capacity (Figure 5.17). The average sediment removal per year from the minor canals is 1,984 m^3, a decrease of 52 m^3 from SIM-4 (Figure 5.18). This reduction in the rate of sediment removal reflects the decrease in ad hoc maintenance capacity from 80% in SIM-4 to 50% in SIM-4.5. Ad hoc maintenance in this scenario begins on day 296, similar to that of SIM-4; this is expected as the incoming sediment did not change between SIM-4 and SIM-4.5, so the sediment depth threshold is reached at roughly the same time. The net sediment deposition at the end of 100 years in this scenario is similar to that of SIM-1. This suggests that with a 67% increase in sediment concentration and only half of tenants conducting maintenance, the net sediment deposition rate in the minor canals is comparable to the ideal scenario under normal design and environmental conditions. According to these findings, ad hoc maintenance can mitigate sediment deposition in the minor canals even with a higher sediment load and half of its full capacity.

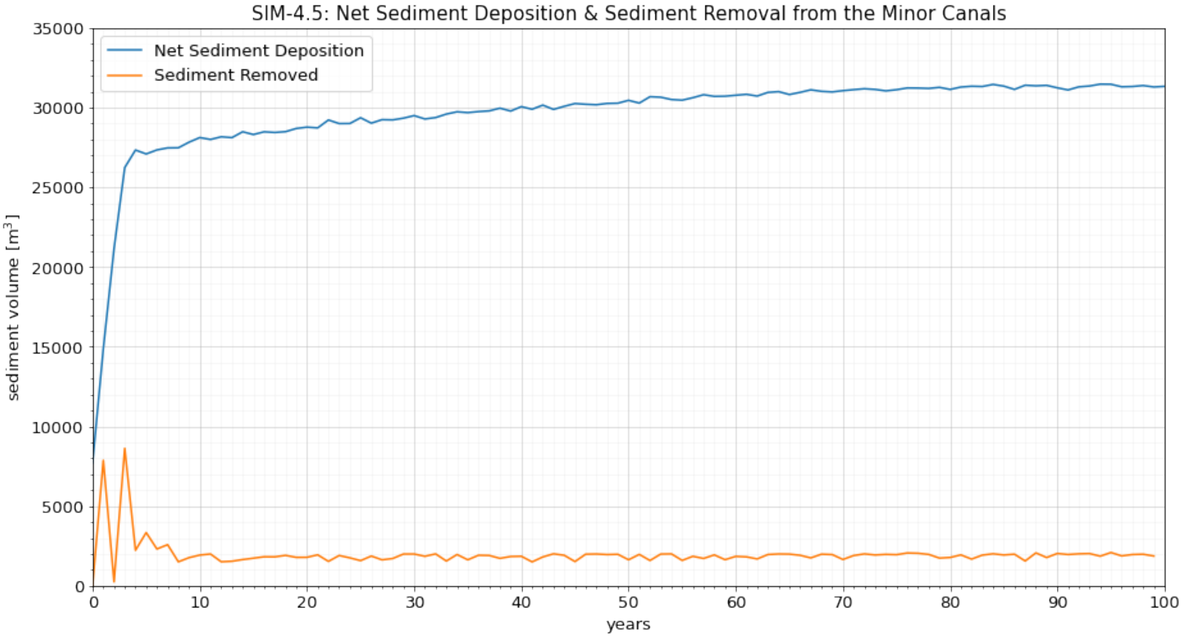


Figure 5.17: SIM-4.5: Net sediment deposition & removal of the minor canals.

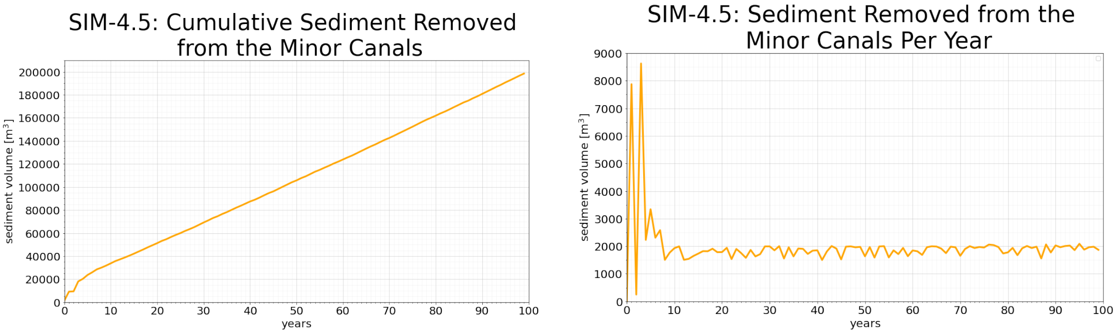


Figure 5.18: SIM-4.5: Sediment removal from the minor canals over time.

The results of SIM-4.5 indicate that even with 50% ad hoc maintenance capacity and a higher sediment load, the amount of net sediment deposition in the minor canals is comparable to the centralized reference scenario (SIM-1). This drives the conclusion that ad hoc maintenance can remove a larger amount of sediment so that the higher sediment load has less impact on sediment deposition in the minor canals.

5.6 Results of SIM-5: Inadequate Maintenance in the Major Canal with Centralized Maintenance in the Minor Canals

In this scenario, the flow of sediment agents and sediment deposition in the Zananda Major Canal behave similarly to that of SIM-1 (Figures 5.19 and 5.20). However, compared to SIM-1, there is a slight increase to 1,449 sediment agents that are in the Zananda Major Canal on average throughout the 100-year simulation. In addition, the average annual sediment deposition in the major canal for this scenario is 5,421 m^3, slightly larger than that of SIM-1 and SIM-2 (Figure 5.20). Because the offtake proportion is reduced in this scenario to simulate a hindrance of water flow from the major canal, the flow of sediment agents from the major canal to the minor canals is stunted. Therefore, slightly more sediment agents remain the major canal. Yet, because the Zananda Major Canal is much larger compared to all the minor canals combined, limiting the offtake proportion to the minor canals has a negligible impact on sediment deposition in the major canal. The GSAB Model focuses on the minor canals; therefore, the reduction of the offtake proportion is sufficient to simulate the reduced flow from the major canal into the minor canals due to sediments blocking water flow. The GSAB Model does not simulate maintenance in the major canal directly, which is why the flow of sediment agents and sediment deposition graphs (Figures 5.19 and 5.20) are similar to those of SIM-1.

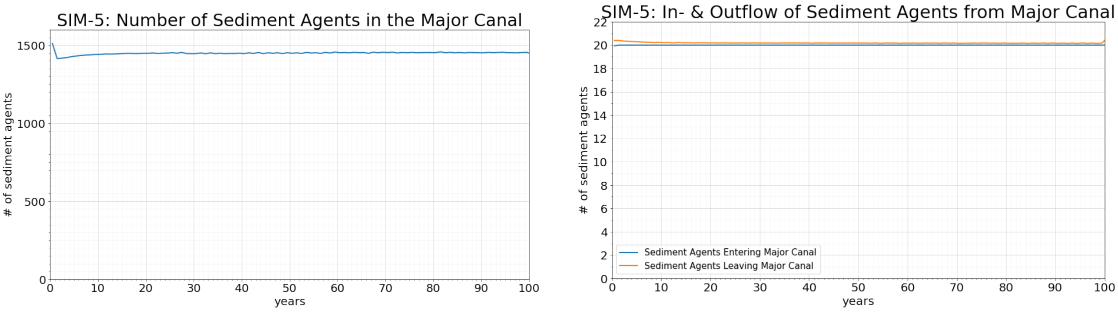


Figure 5.19: SIM-5: Sediment agents in the Zananda Major Canal.

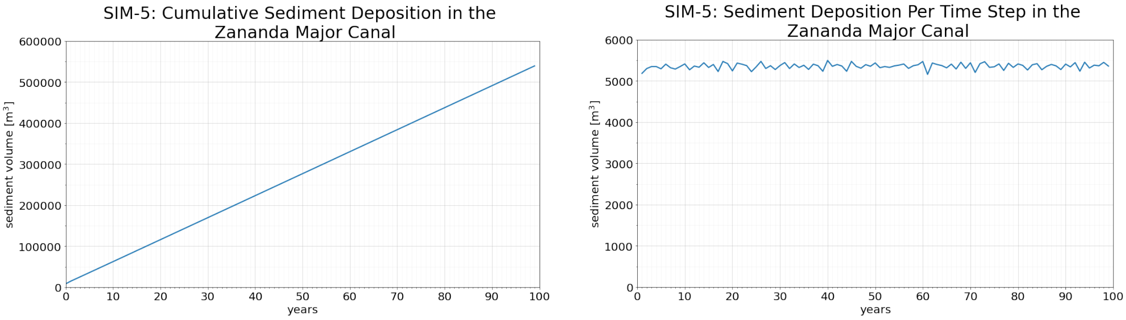


Figure 5.20: SIM-5: Sediment deposition in the Zananda Major Canal.

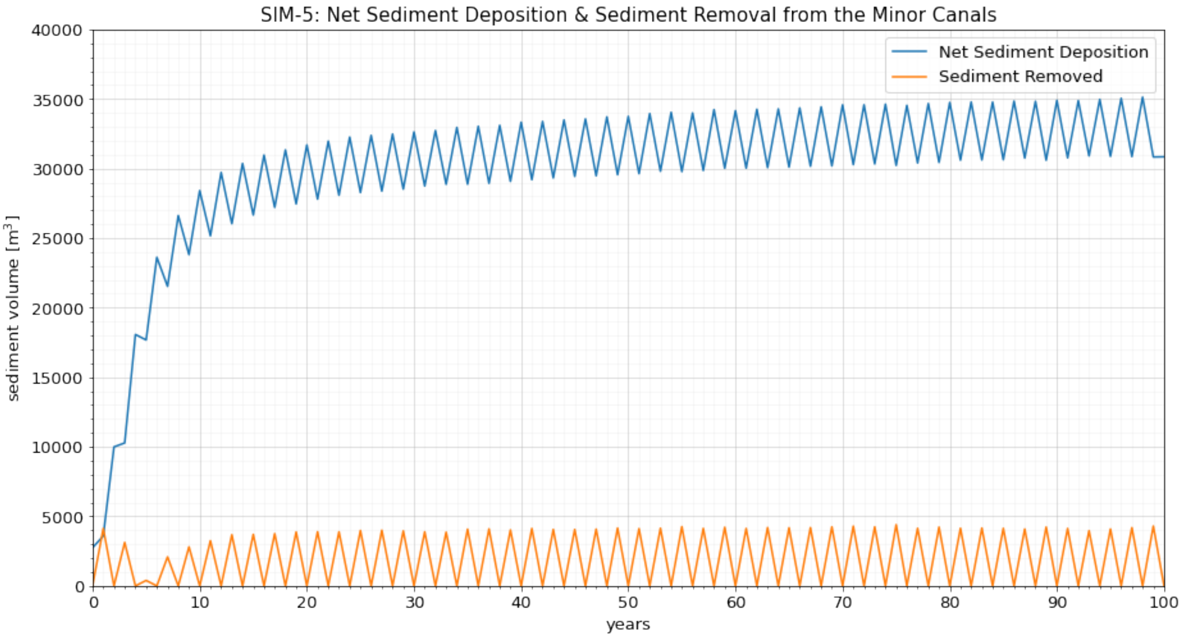


Figure 5.21: SIM-5: Net sediment deposition & removal of the minor canals.

At the end of the 100-year simulation, the net sediment deposition in the minor canals is 30,844 m^3 (Figure 5.21), which is the best result of all the centralized maintenance scenarios so far (SIM-1, SIM-3, and SIM-5). The average net sediment deposition is 299 m^3 per year in SIM-5. Because the inflow is hindered at the offtakes from the Zananda Major Canal, there is less sediment entering the minor canals from the major canal in this scenario. The average sediment removal per year is 1,937 m^3 over the 100-year simulation. This suggests that limiting the inflow of sediment into the minor canals is more effective at controlling sediment deposition than conducting centralized maintenance after sediment have already entered the minor canals. With fewer sediment agents in the minor canals, less maintenance is required to achieve comparable sediment deposition rates to the reference scenario. Still, the results show that reducing the inflow from the major canal does not fully mitigate net sediment deposition in the minor canals. This indicates that maintenance in the major canal is not as crucial as in the minor canals. The minor canals are much smaller and accumulate sediment faster than the major canal. Moreover, the major canal has drainage, while the minor canals do not. The only way to remove sediment in the minor canals is to desilt.

5.7 Results of SIM-6: Inadequate Maintenance in the Major Canal with Ad hoc Maintenance in the Minor Canals

In SIM-6, the flow of sediment agents and sediment deposition in the Zananda Major Canal behave similarly to those of SIM-5 (Figures 5.22 and 5.23). On average, there are 1,445 sediment agents in the Zananda Major Canal throughout the 100 years simulation, and the average annual sediment deposition is 5,420 m^3 (Figure 5.23). Again, this slight increase in sediment agents from SIM-2 and SIM-4 is caused by a disruption of flow from the major canal to the minor canals, so more sediment agents stay in the major canal.

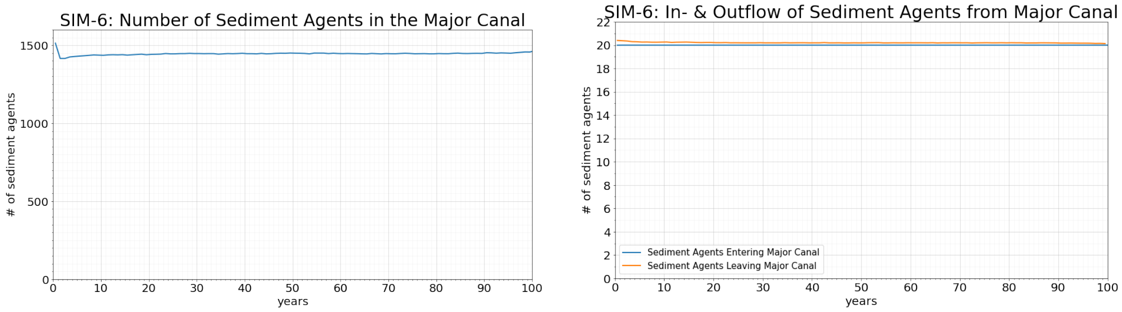


Figure 5.22: SIM-6: Sediment agents in the Zananda Major Canal.

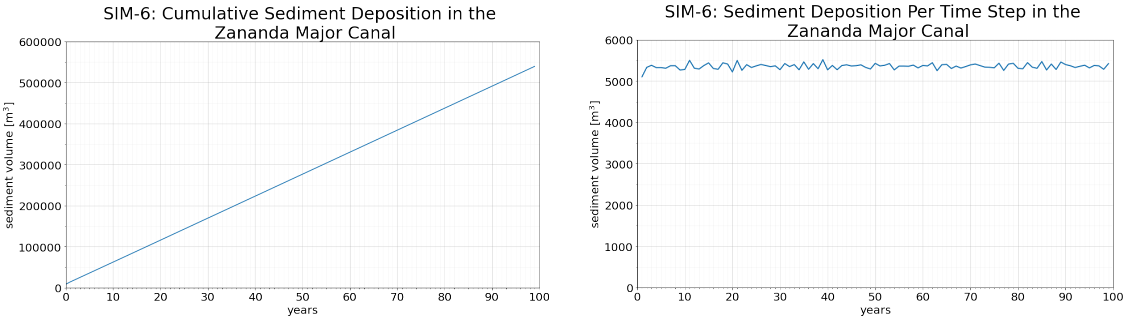


Figure 5.23: SIM-6: Sediment deposition in the Zananda Major Canal.

At the end of the 100-year simulation, the net sediment deposition in the minor canals is 29,915 m^3 (Figure 5.24), which is the best result of all the scenarios so far.

On average, the annual net sediment deposition is 263 m^3. The average sediment removal per year is 1,965 m^3 (Figure 5.25), the lowest sediment removal rate across all ad hoc maintenance scenarios so far (SIM-2, SIM-4, and SIM-6). Because there are fewer sediment agents entering the minor canals, less maintenance is required to achieve lower sediment deposition rates. In this scenario, ad hoc maintenance begins on day 756 (day 26 of the third year); like SIM-2, ad hoc maintenance begins in the third year. Though ad hoc maintenance under design conditions (SIM-2) begins at roughly the same time as in this scenario, there is a lower annual sediment removal rate in SIM-6 compared to SIM-2 while the net sediment deposition in SIM-6 is lower than that of SIM-2. This suggests that regulating the inflow of sediment into the minor canals results in less sediment accumulation over time while requiring less ad hoc maintenance. Moreover, it supports the conclusion that with ad hoc maintenance, the improvement in net sediment deposition in the minor canals is better realized with a restriction of flow compared to centralized maintenance. Nevertheless, a lack of maintenance in the major canal has little impact on sedimentation in the minor canals in the GSAB Model. As mentioned in Section 5.6, maintenance in the minor canals is more crucial than in the major canal because the minor canals are smaller and accumulate sediment much quicker. Additionally, the major canal has drainage that helps to remove sediment while sediment in the minor canals can only be removed through maintenance.

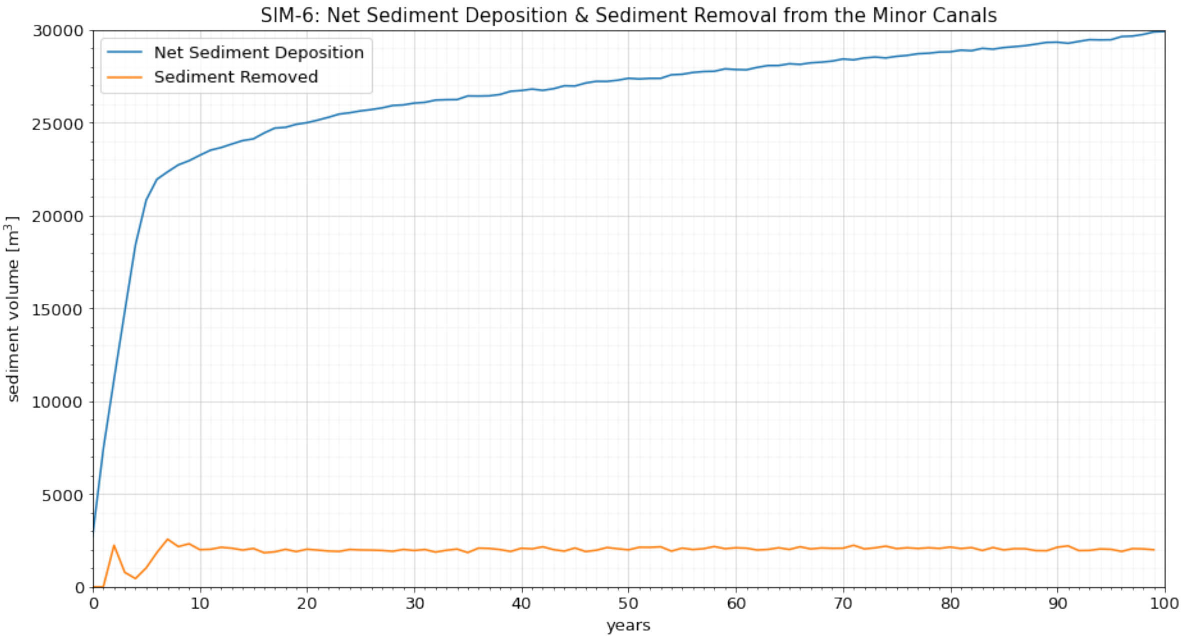


Figure 5.24: SIM-6: Net sediment deposition & removal of the minor canals.

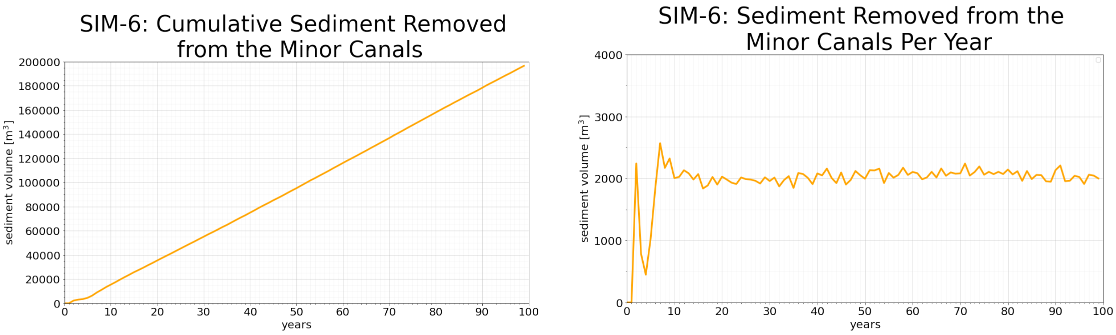


Figure 5.25: SIM-6: Sediment removal from the minor canals over time.

5.8 Results of SIM-7: Increased Inflow from the Major Canal with Centralized Maintenance in the Minor Canals

On average, the Zananda Major Canal has 1,439 sediment agents throughout the 100-year simulation like SIM-1, SIM-2, SIM-4, and SIM-4.5 (Figure 5.26). The average annual sediment deposition in the major canal is 5,417 m^3 like SIM-1 and SIM-2 (Figure 5.27). However, compared to SIM-1 and SIM-2, there is higher variation in the amount of sediment deposition from year to year (Figure 5.27 vs. Figures 5.2 and 5.5). A higher offtake proportion in this scenario means that there is more randomness in the model (see Section 3.4). The sediment agents move from the major canal into the minor canal only when a randomly generated number between zero and 100 is less than the offtake proportion. A higher offtake proportion means that there is a higher probability that they will decide to enter the minor canals. The sediment agents show more randomness in their choice to move into the minor canals from the major canal if the offtake proportion is increased.

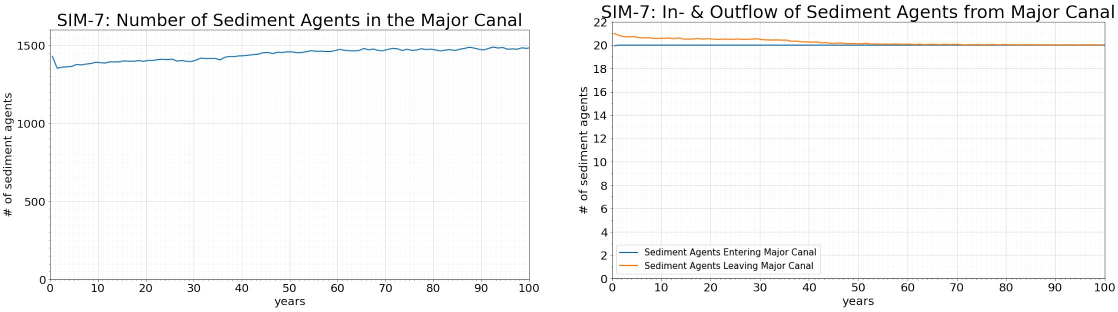


Figure 5.26: SIM-7: Sediment agents in the Zananda Major Canal.

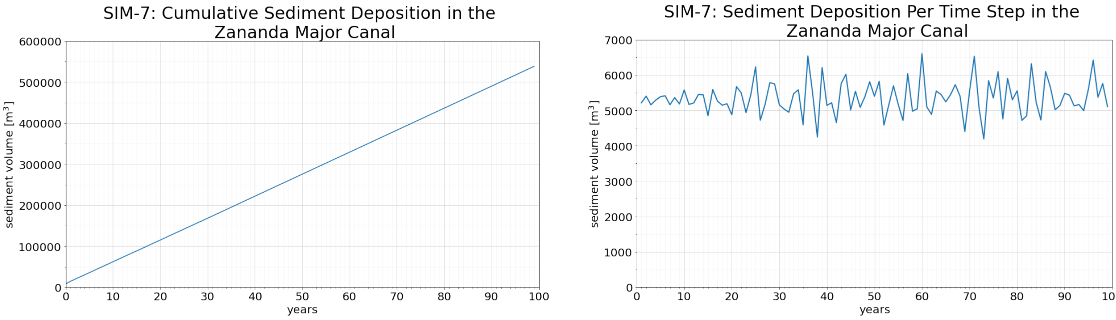


Figure 5.27: SIM-7: Sediment deposition in the Zananda Major Canal.

At the end of the 100-year simulation, the net sediment deposition in the minor canals is 32,054 m^3, and the average annual net sediment deposition is 312 m^3 (Figure 5.28). The average annual sediment removal rate is 1,958 m^3 (Figure 5.28). This represents a 1% increase from the results of SIM-1, implying that an increased inflow of sediment agents into the minor canals has little impact on the net sediment deposition rate. As shown in the "no maintenance" simulation of an increased inflow from the Zananda Major Canal (see Section 4.2.4), a higher offtake proportion does not increase sediment deposition in the minor canals. This could be due to the small width of the offtakes in the GSAB Model, which limits the number of sediment agents that are able to move onto the offtake's patches, even if the offtake proportion increases. Therefore, the capacity of centralized maintenance can still mitigate the amount of net sediment deposition in the minor canals.

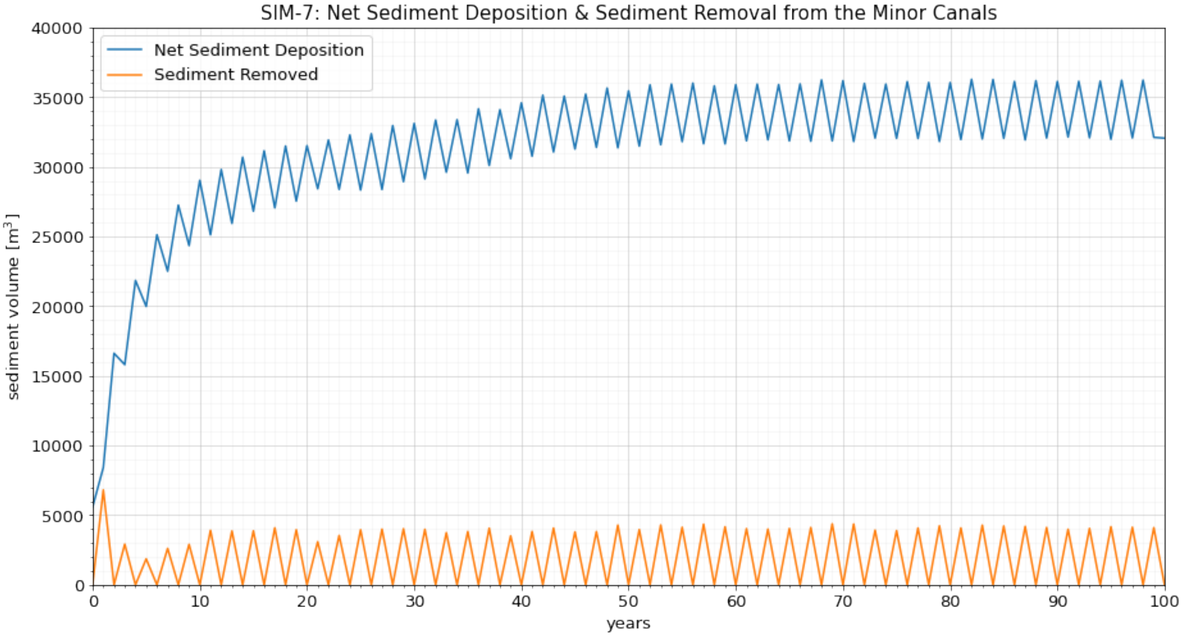


Figure 5.28: SIM-7: Net sediment deposition & removal of the minor canals.

The results of SIM-7 suggest that allowing more sediment agents to enter the minor canals by increasing the offtake proportion has little impact on the net sediment deposition. Centralized maintenance still has the capacity to maintain a steady level of sediment removal. It is possible that a higher water discharge rate from the main canals does not trickle down to the minor canals; the weir control structures are assumed to be functional (see Section 3.5.1) which helps to control the water and sediment inflow into the minor canals. In reality, the functionality of the weirs is influenced by sediment deposition and water level (Osman, 2015). Historically, illegal withdrawal of water from the minor canals also changed water levels and disrupted water supply downstream (Osman, 2015). The assumptions made in the GSAB Model could have resulted in an underestimation of the net sediment deposition in this scenario. Nevertheless, the results of SIM-7 indicate the importance of the hydraulic structures; if functioning properly, they can potentially regulate the flow so that an increased water flow rate does not drastically increase net sediment deposition in the minor canals. In this case, the outcome of SIM-7 provides evidence that centralized maintenance has sufficient capacity to mitigate sediment accumulation.

5.9 Results of SIM-8: Increased Inflow from the Major Canal with Ad hoc Maintenance in the Minor Canals

The flow of sediments into and out of the Zananda Major Canal in SIM-8 is similar to that of SIM-7 (Figure 5.29 and 5.30). Like SIM-7, the average number of sediment agents and the average annual sediment deposition in the major canal are 1,439 and 5,417 m^3, respectively. Again, the variation in the amount of sediment deposition from year to year shows that the higher offtake proportion generates more randomness in the choices that sediment agents can make on whether to move from the major canal into the minor canals.

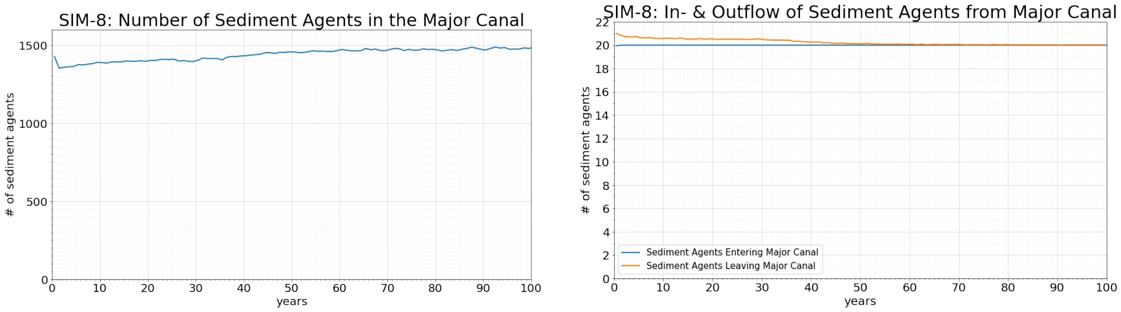


Figure 5.29: SIM-8: Sediment agents in the Zananda Major Canal.

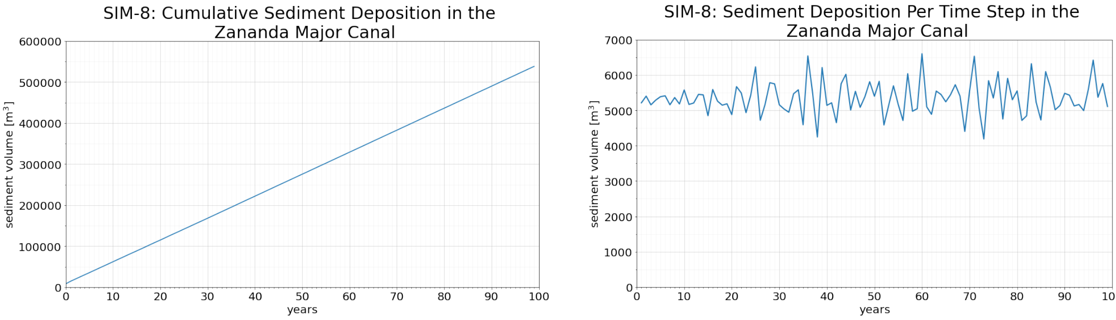


Figure 5.30: SIM-8: Sediment deposition in the Zananda Major Canal.

At the end of the 100-year simulation, the net sediment deposition in the minor canals is 30,817 m^3; the average annual net sediment deposition is 284 m^3 (Figures 5.31 and 5.32). The average annual sediment removal rate is 1,990 m^3 (Figure 5.32). This is comparable to the results of previous ad hoc maintenance scenarios, implying that ad hoc maintenance can mitigate the impact of a higher water inflow. In this scenario, ad hoc maintenance begins on day 91 of the second year. The sediment depth threshold is reached about a half a year later than in SIM-4 and SIM-4.5. This suggests that an increased inflow has a smaller impact on net sediment deposition in the minor canals than an increased sediment concentration. Yet, the assumptions made in the GSAB Model as discussed in Section 5.8 may have underestimated the impact of increased water flow on sediment deposition in the minor canals.

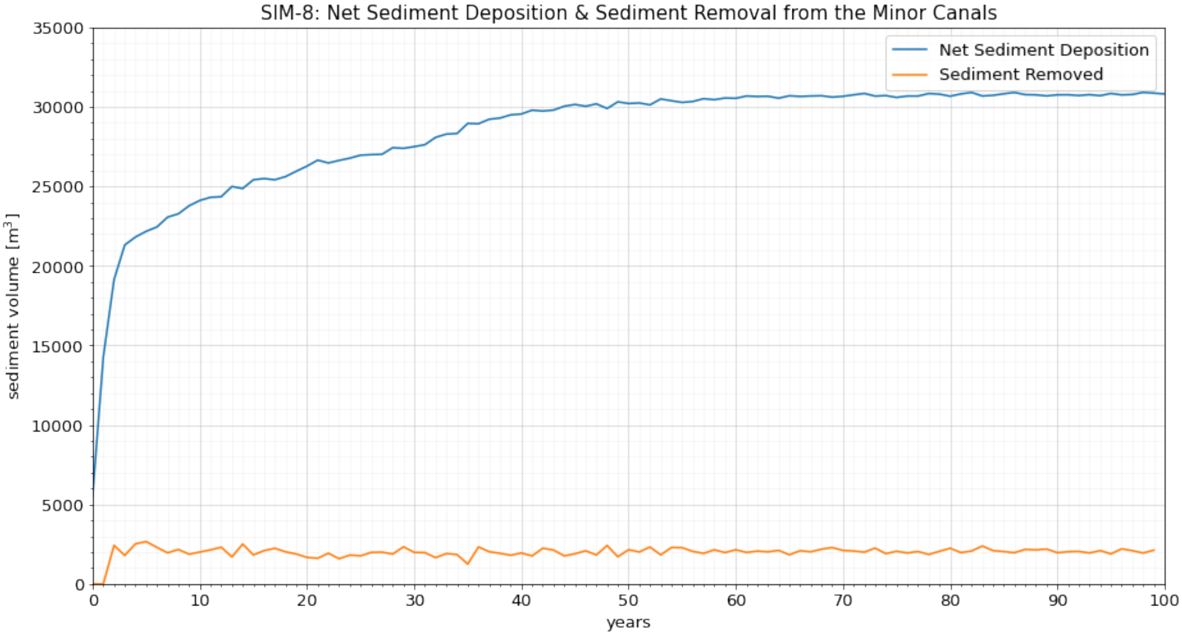


Figure 5.31: SIM-8: Net sediment deposition & removal of the minor canals.

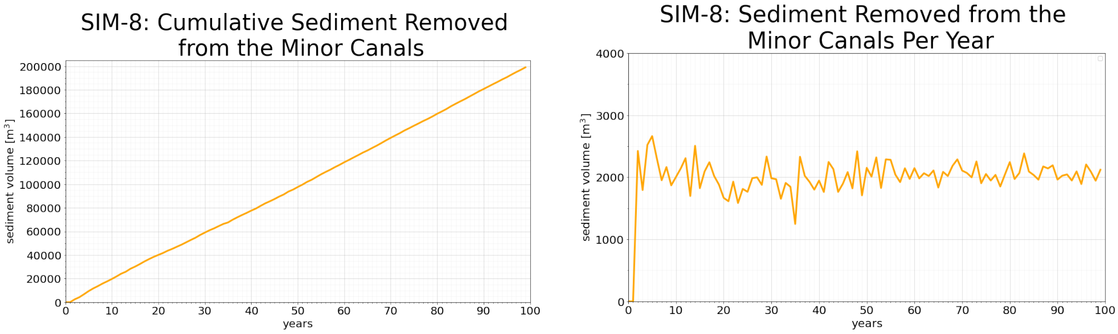


Figure 5.32: SIM-8: Sediment removal from the minor canals over time.

5.10 Scenario Analysis Results Summary

In all scenarios, there remains a net amount of sediment deposition in the minor canals after the 100-year simulation (Figure 5.33 and 5.34). The results of the scenario analysis present evidence that ad hoc maintenance leaves less net sediment deposition in the minor canals after 100 years compared to centralized maintenance (Figure 5.33). Nevertheless, the most notable result is that of SIM-3, which yields the highest net sediment deposition in the minor canals of all the scenarios (Figure 5.33). This suggests that an increased sediment concentration poses the biggest threat to sedimentation in the minor canals and that centralized maintenance does not effectively mitigate it. This is consistent with the main criticism of the Lacey regime theory design of the Gezira canals that it does not accommodate higher sediment loads (see Section 2.2). The model results drive the conclusion that centralized maintenance does not remove enough sediment to unclog the canals which happens quickly under high sediment loads.

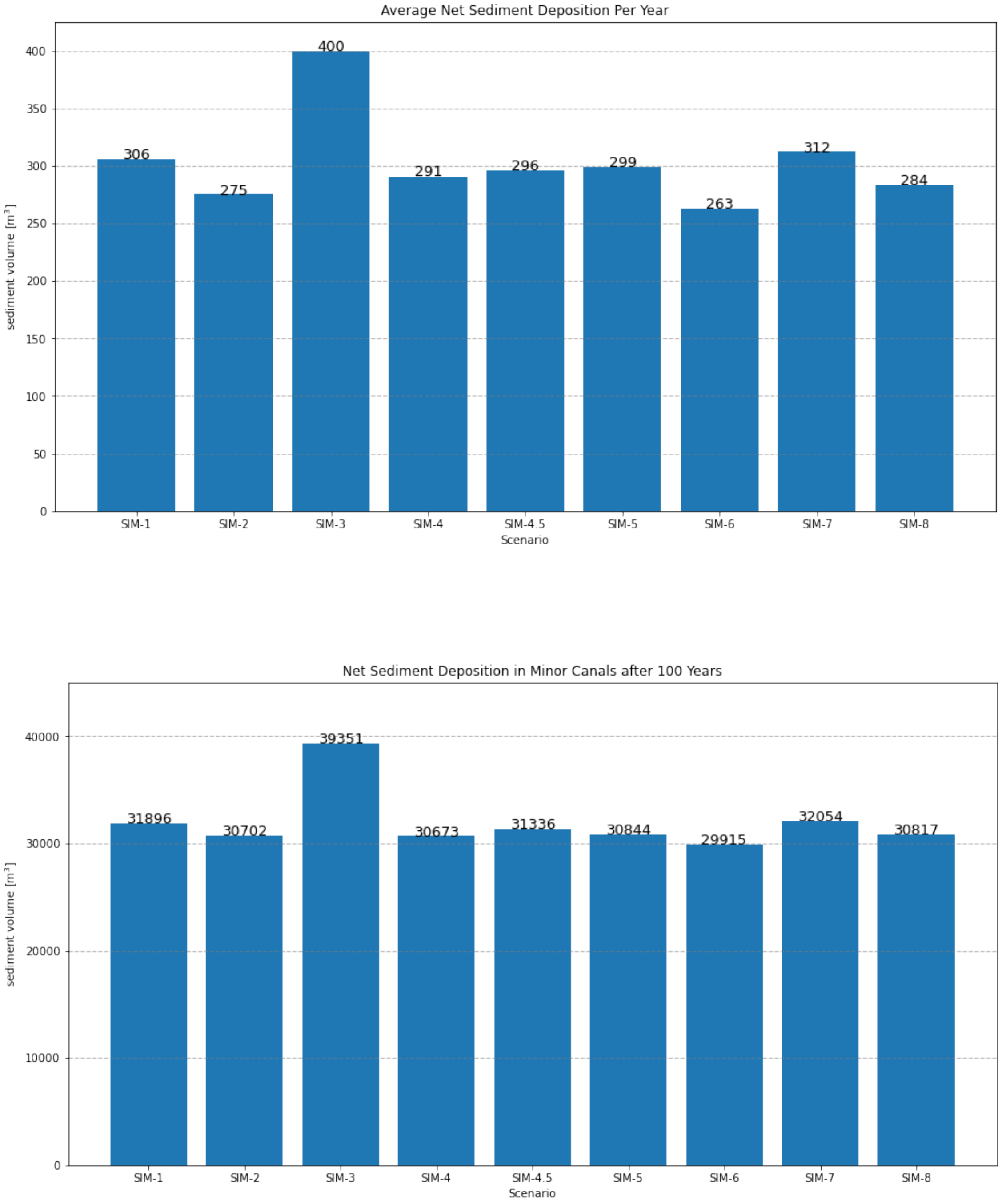


Figure 5.33: Net sediment deposition after 100 years and average annual net sediment deposition in minor canals for all scenarios (continued).

In addition, the results of the GSAB Model show that ad hoc maintenance produces less variation in the net sediment deposition from year to year than centralized maintenance, as ad hoc maintenance can be conducted throughout the year and in any given year while centralized maintenance happens biennially (Figures 5.34). In Figure 5.34, the peaks and valleys in the lines for centralized maintenance scenarios

(SIM-1, SIM-3, SIM-5, and SIM-7) reflect that centralized maintenance only occurs every two years. On the years that centralized maintenance is conducted, the net sediment deposition in the minor canals declines because sediment is removed. Then, the net sediment deposition increases as the canals are reopened until two years later when centralized maintenance happens again. On the other hand, the lines for ad hoc maintenance scenarios (SIM-2, SIM-4, SIM-4.5, SIM-6, and SIM-8) in Figure 5.34 are smoother than the centralized maintenance scenarios. This shows that ad hoc maintenance occurs leaves a more consistent amount of net sediment deposition from year to year.

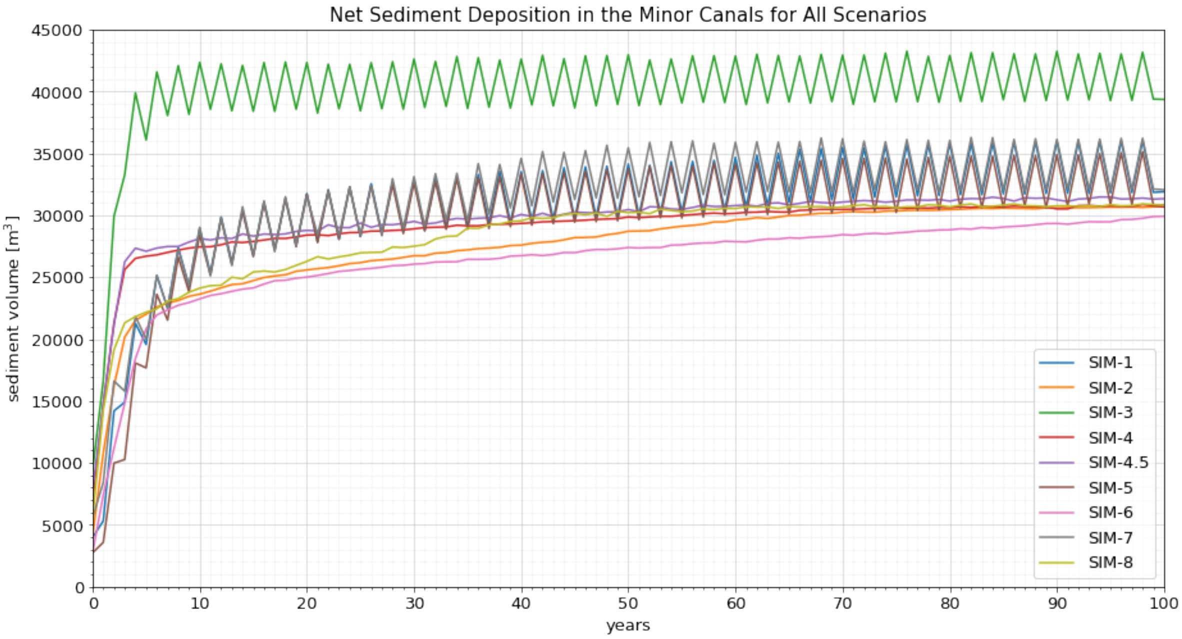


Figure 5.34: Net sediment deposition in minor canals for all scenarios.

The scenario simulations of the GSAB Model indicate that both centralized and ad hoc maintenance can maintain a degree of stability in the amount of net sediment deposition in the minor canals (Figure 5.34). However, the high net sediment deposition in SIM-3 suggests that an increased sediment concentration causes the minor canals to be clogged quickly, rendering centralized maintenance inadequate for unclogging the excess sediment in the canals. This is supported by the higher net sediment deposition rate in the minor canals for SIM-3, while the other scenarios show more similarity in their net sediment deposition rate (Figure 5.34). The results present evidence that ad hoc maintenance with at least 50% capacity performs better than centralized maintenance at 100% capacity even under worse environmental conditions. Ad hoc maintenance in the GSAB Model produces lower average net sediment deposition rates that centralized maintenance (Figure 5.33). Even with increased erosion from upstream areas (represented by SIM-4), a lower maintenance capacity (represented by SIM-4.5), and higher inflow from the major canal (represented by SIM-8), ad hoc maintenance yields less net sediment deposition in the minor canals than centralized maintenance under design conditions (SIM-1) (Figure 5.33). Furthermore, the results of the scenario analysis indicate that in the long term, restricting the inflow of sediment into the minor canals is effective not only for decreasing the net sediment deposition but also for reducing the necessary maintenance capacity to do so (Figures 5.34 and 5.35).

The peaks and valleys in the graphs for SIM-1, SIM-3, SIM-5, and SIM-7 in Figure 5.35 reflect that centralized maintenance only occurs every two years. During the years when centralized maintenance occurs, the amount of sediment removal is greater than zero; on the off years, the amount of sediment removal drops to zero (SIM-1, SIM-3, SIM-5, and SIM-7 graphs in Figure 5.35). These peaks and valleys correspond to the centralized maintenance scenarios in Figure 5.34, indicating that the net sediment deposition declines by the amount of sediment removed in Figure 5.35. On the other hand, ad hoc maintenance can be triggered whenever sediment deposition is noticed by the tenants; this is simulated by the sediment depth threshold ($h_{s,\%}$) in the GSAB Model. Ad hoc maintenance can occur in any year unlike centralized maintenance.

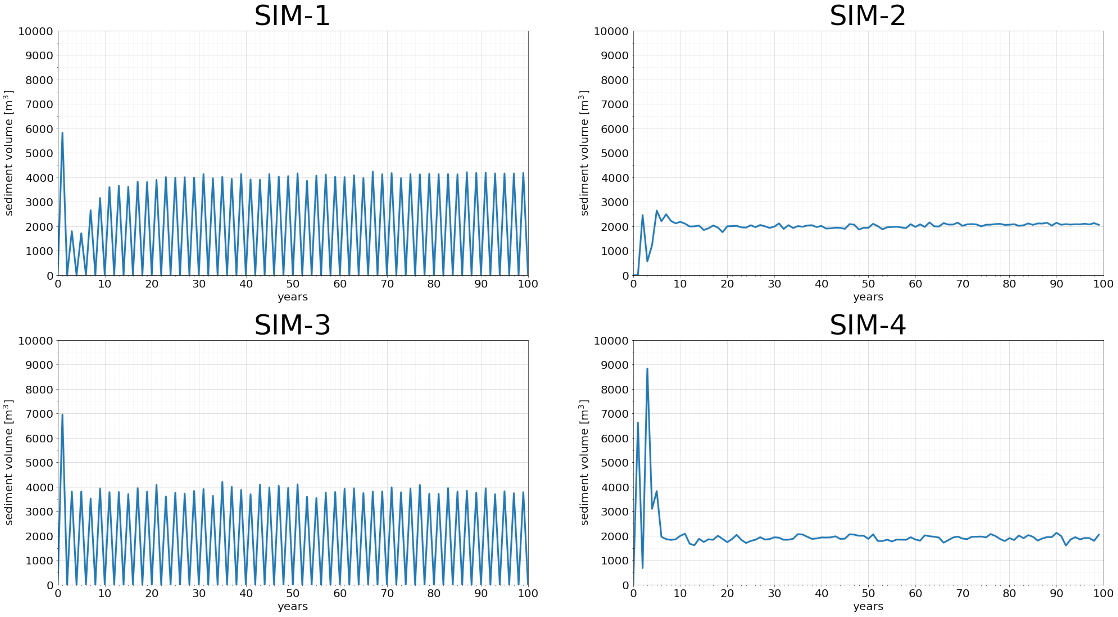


Figure 5.35: Annual sediment removal from all minor canals for each scenario.

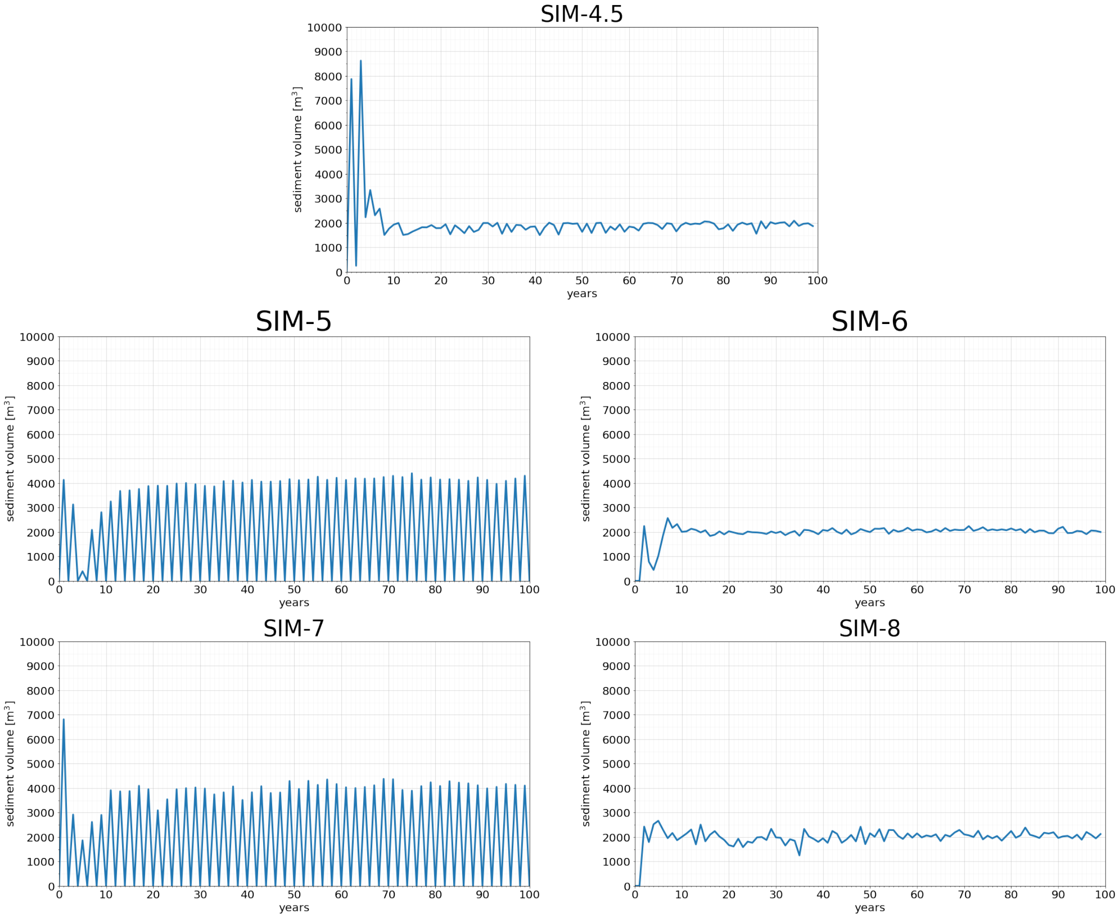


Figure 5.35: Annual sediment removal from all minor canals for each scenario (continued).

The results of the scenario analysis present evidence that ad hoc maintenance has more flexibility to adjust to desilting requirements under various environmental conditions compared to centralized maintenance. Despite a higher sediment concentration (SIM-3 and SIM-4) and increased inflow from the major canal (SIM-7 and SIM-8), the average annual sediment removal for ad hoc maintenance scenarios is higher than that of centralized maintenance scenarios (Figure 5.36). In the GSAB Model, the starting year for ad hoc maintenance is flexible as it is based on the sediment depth threshold ($h_{s,\%}$). The scenario results indicate that the higher sediment concentration and increased inflow can be accommodated by an earlier start to ad hoc maintenance (Figure 5.36). For example, in SIM-3, SIM-4, and SIM-4.5 when there is increased sediment concentration, ad hoc maintenance can remove the additional inflow of sediment quickly (SIM-4), while centralized maintenance (SIM-3) maintains a similar rate of removal as the reference scenario (SIM-1) (Figure 5.35). Furthermore, the outcome of SIM-4.5 implies that even with less capacity, ad hoc maintenance still mitigates the impact of sediment deposition. It is possible that during British colonial rule, there was a higher centralized maintenance capacity than calculated for the GSAB Model because the equipment available as documented by Plusquellec (1990) was divided over fewer minor canals (see Section 3.6.3). However, the GSAB Model assumes a constant 100% centralized maintenance capacity over the entire 100-year simulation, though it is likely that there may be points in time when not all equipment was available for maintenance. Given these assumptions, the results suggest that centralized maintenance cannot remove excess sediment that are clogging the minor canals, causing a higher net sediment deposition rate especially under higher sediment loads.

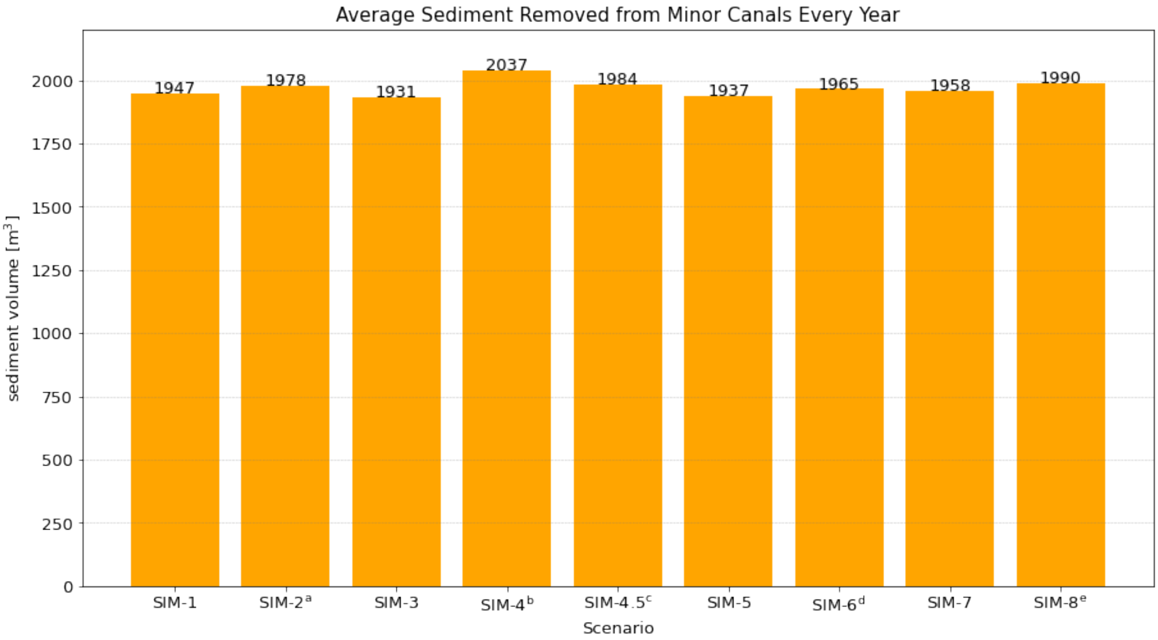


Figure 5.36: Average sediment removal per year for all scenarios.

[a] For SIM-2, ad hoc maintenance begins on day 788 (day 58 of the third year).
[b] For SIM-4, ad hoc maintenance begins on day 297 (mid-October of the first year).
[c] For SIM-4.5, ad hoc maintenance begins on day 296 (mid-October of the first year).
[d] For SIM-6, ad hoc maintenance begins on day 756 (day 26 of the third year).
[e] For SIM-8, ad hoc maintenance begins on day 456 (day 91 of the second year).

Chapter 6

Discussion and Conclusion

6.1 Discussion

Pre-independence: 1925-1956

The results of the GSAB Model indicate that since the opening of the Gezira Scheme until Sudan's independence, sediment accumulation in the minor canals was a major issue. Centralized maintenance still left a substantial amount of net sediment deposition in the minor canals of the model world (see Figure 2.2 and the results of SIM-1 in Section 5.1). This suggests that the full capacity of centralized maintenance did not adequately remove all sediment that entered the minor canals. Even under ideal environmental conditions as dictated by the Lacey regime theory design, centralized maintenance in the GSAB Model could not fully remove all the sediment deposited the minor canals. These results do not support the claim that sedimentation was only a problem after independence (see Section 2.4). The regime theory method of designing the canals may not have lived up to its promise of producing non-silting canals in the Gezira canals (see Section 2.2).

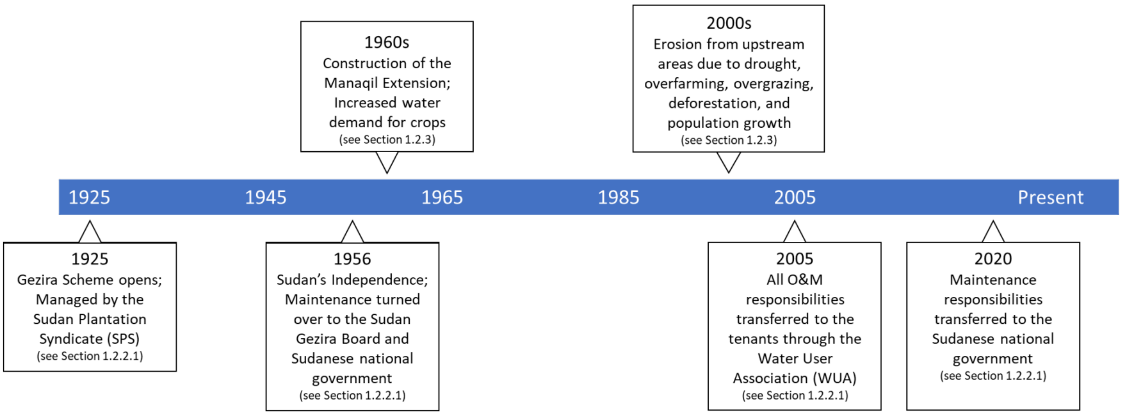


Figure 2.2: Timeline of key management stakeholders and environmental factors impacting sedimentation in the Gezira Scheme.

In addition, the night storage system was not modeled in the GSAB Model (see Sections 2.1.3 and 3.5.1), which could have caused an underestimation of sediment deposition in the centralized maintenance scenarios; Osman (2015) found that the night storage system actually contributed to more sediment deposition in the minor canals compared to a continuous flow system. The results of SIM-1 indicate that centralized maintenance efforts may not have been sufficient even during the pre-independence period when the canals were thought to have been operating as designed. Even with less water and sediment inflow to the minor canals as simulated in SIM-5 (see Section 5.6), centralized maintenance did not fully mitigate sediment accumulation in the minor canals in the GSAB Model. This implies that when Sudan gained independence in the 1950s, excessive amounts of sediment had already accumulated in the minor canals.

Furthermore, the GSAB Model assumes a constant maintenance capacity over time; the centralized maintenance capacity was set to 100% over the entire 100-year simulation (see Table 3.5). However, some desilting equipment might have been repurposed for World War II, leading to a smaller maintenance capacity for the Gezira Scheme. To fully reconstruct the historical sedimentation trajectory, future expansions of GSAB Model should allow for adjustable bed profiles and maintenance capacities by decade to reflect any potential changes in the availability of equipment.

Post-independence in the 20th century: 1956-2000s

After Sudan gained independence, maintenance responsibilities transitioned to the Sudanese government and the SGB (see Figure 2.2 and Section 2.3.1). The results of the GSAB Model suggest that the Sudanese government inherited a canal system that already had excessive sediment accumulation in the minor canals (see previous section on the discussion of the pre-independence situation). When incoming water flow increased in the 1960s due to the Manaqil Extension and higher water demand (see Figure 2.2), the net sediment deposition increased only slightly compared to the scenario under design conditions (see the results of SIM-7 in Section 5.8). While it is possible that the effects of a higher water flow rate in the main canal do not trickle down to the minor canals, the GSAB Model makes assumptions about the weir control structures at the offtakes that could have impacted the results of SIM-7. First, the GSAB Model assumes the weirs are operating as designed (see Section 3.5.1). The regulation of flow by the weirs was calibrated according to Lacey's regime theory method that assumes a constant discharge and water level. However, the weirs are sensitive to sediment deposition in the minor canals and fluctuations in water level in the real world (see Section 3.5.1). The increased inflow from the major to the minor canals was modeled by a higher offtake proportion; the GSAB Model does not account for the impacts of fluctuating water levels on the function of the weirs. In reality, changing water levels makes it hard to maintain the intended water and sediment inflow into the minor canals (Osman, 2015).

In addition, the GSAB Model does not model any other aggravating factors that worsen sediment deposition, such as aquatic weed formation. Also, sediment deposition and clogging of the weir control structures cause the water level to rise above the ideal Lacey regime theory design; this results in an overflow of water and sediment beyond the canal banks (Osman, 2015). The GSAB Model does not model this overflow (see Section 3.5.1). These assumptions could have contributed to an underestimation of the impact of an increased water inflow in SIM-7 and SIM-8. Because the GSAB Model does not model water flow directly but through the abstraction of a sediment agent, the offtake proportion parameter was used as a proxy of water inflow, as it regulates the number of sediment agents that can enter the minor canals from the major canal in the model. Using sediment agents in this study limits the direct representation of water flow.

Increased erosion and ad hoc maintenance: 2000s-2020

At the start of the 21^{st} century, the Gezira Scheme experienced a higher sediment load due to erosion from upstream areas; then, in 2005, maintenance responsibilities transitioned to the tenants who conducted manual, ad hoc maintenance (see Figure 2.2). SIM-4 and SIM-4.5 resemble this scenario. However, the simulations for SIM-4 and SIM-4.5 began with empty minor canals (see Section 5.4); by 2005, it is likely that increased water inflow from the Manaqil Extension and crop production in the 1960s along with upstream erosion in the 2000s left more accumulated sediment in the minor canals than depicted by the results of SIM-4 and SIM-4.5. Nevertheless, the results of SIM-3 suggest that centralized maintenance cannot effectively unblock the minor canals that fill with sediment quickly due to the higher sediment load (see Section 5.3). Therefore, the tenants could have inherited a canal system with an excessive amount of sediment already deposited in the canals by 2005. This does not support the claim that the transfer of management responsibilities from centralized management to the tenants contributed to the deterioration of the canals. Based on the results of the GSAB Model, it is likely that tenants struggled to desilt effectively when they became responsible for maintenance in 2005; by then, the minor canals had already been clogged with sediment.

The results of the GSAB Model indicate that a higher sediment load from upstream erosion poses the biggest threat to the canal system, outweighing even the impact of more water inflow (Section 5.10). The high sediment load clogs the canals quickly. In turn, this hinders the canal's conveyance capacity and creates inequality in water distribution (Osman, 2015). Yet, even with the lower capacity (see the results of SIM-4.5 in Section 5.5), ad hoc maintenance seems to be more effective at unclogging the canals, enabling desilting efforts to keep up with the amount of inflowing sediment into the minor canals. Future research should investigate how limited maintenance in upstream minor canals impacts sediment accumulation and water supply downstream while varying the maintenance capacity in certain time periods. For instance, lower ad hoc maintenance capacities can be simulated to represent fewer tenants being available or willing to desilt.

6.2 Conclusion

This research assesses the effect of various environmental factors and maintenance strategies on sedimentation in the minor canals of the Gezira Scheme. The research sub-questions as shown below are addressed to answer the main research question: *How do different environmental conditions and maintenance strategies impact sediment deposition in the minor canals of the Gezira Irrigation Scheme?*

Sub-question #1: What theories underpinned the original design of the Gezira canals?

The Gezira canals were designed according to the regime theory method, where Lacey's equations were used. This method determines the canal dimensions assuming that the canal's geometry does not change over typical water years and that a constant water level is maintained. The Gezira Scheme runs on gravity flow where main canals supply water to smaller, minor canals.

Sub-question #2: What impact did different environmental factors have on sedimentation in the Gezira canals?

Two main environmental factors have had an impact on sedimentation in Gezira's history: erosion from upstream areas and increased water inflow. Erosion from upstream areas like the Ethiopian Highlands began in the 2000s due to overgrazing, deforestation, overfarming, drought, and population growth. This caused higher sediment loads to enter the Gezira canals.

An increase in the water flow rate occurred in the 1960s when the Managil Extension was constructed and more crop production increased the water demand. Because fine sediment are transported in suspension, higher water flow rates transport more sediment into the canals. This increases the chance for more sediment deposition and jeopardizes the water supply to downstream areas. Clogged canals limit the flow of water and may cause tension between tenants who receive an unequal distribution of water.

Sub-question #3: What impact did different human factors, namely maintenance strategies, have on sedimentation in the Gezira canal system?

Two types of maintenance strategies were used in Gezira's history: centralized maintenance and ad hoc maintenance. Centralized maintenance refers to centrally managed desilting efforts established the British during their colonial era. Ad hoc maintenance refers to manual, tenant-run maintenance where the WUAs became responsible for all operations and management in 2005.

Successful management of the Gezira Scheme is a complex endeavor where human and physical factors intertwine. Because of a lack of systematic study and measurement of sedimentation in the Gezira Scheme, many claims have emerged that attempt to explain why sedimentation has worsened over the last century. Specifically, the pivotal point of worsening sedimentation is thought to be decolonization, when the Sudanese gained independence in the 1950s and O&M of the Gezira Scheme transitioned from the British to the Sudanese.

Sub-question #4: How can environmental and human factors be conceptualized into an ABM?

The GSAB Model uses elevation data and a schematic map of the Zananda Major Canal and its seven minor canal offtakes to set up the model interface. Sediment agents are placed in the major canal upon setup while the minor canals start off empty. The sediment agents flow downstream to mimic gravity flow. When the simulation begins, the GSAB Model executes three "Go" procedures: 1. Create continuous sediment flow, 2. Transport sediment, and 3. Deposit sediment and conduct maintenance.

In the first "Go" procedure, the model simulates continuous sediment flow based on uniform open channel flow at constant water level for trapezoidal canals. Sediment agents are created at point K57 in the Zananda Major Canal to represent the source of water flow.

In the second "Go" procedure, sediment agents move from higher elevation canal patches to lower elevation ones. This simulates gravity flow. At the offtakes to the minor canal, the flow of sediment agents is regulated by an offtake proportion parameter, which represents the function of the weir control structures that limit the flow from the major canal to the minor canals.

In the third and final "Go" procedure, sediment agents deposit sediment onto the canal patches and maintenance is conducted. Sediment deposition is based on the deposition flux, which is determined by multiplying the settling velocity with the sediment concentration. The user can select between three maintenance scenarios: 1. No maintenance, 2. Centralized maintenance, and 3. Ad hoc maintenance. The "no maintenance" scenario means that the minor canals are not desilted; therefore, sediment accumulates in the minor canals until they reach their maximum volume. Centralized maintenance refers to centrally managed maintenance that occurs every two years between April and June when the canal system is closed for the off season. This reflects the maintenance scenario established by the British colonists when the Gezira Scheme was constructed in the 1920s. Ad hoc maintenance refers to maintenance conducted in a decentralized manner by the tenants themselves. This represents desilting operations when maintenance responsibilities were transferred to the WUAs in 2005. Ad hoc maintenance occurs at any time during the year whenever the tenants notice sediment piling up in the canals and restricting their water supply.

Sub-question #5: What scenarios can be tested by an ABM to pinpoint the cause of sedimentation in the Gezira canals?

Nine scenarios were simulated in this research according to Table 3.4.

SIM #	Maintenance Strategy	Scenario Description
SIM-1	Centralized	Design conditions where Lacey's regime theory values are used for input parameters
SIM-2	Ad hoc	
SIM-3	Centralized	Increased sediment concentration due to erosion from upstream areas caused by overagriculture, population growth, drought, and deforestation
SIM-4	Ad hoc	
SIM-4.5	Ad hoc (at lower capacity)	
SIM-5	Centralized	Inadequate maintenance in the major canal causing a blockage of flow into the minor canals
SIM-6	Ad hoc	
SIM-7	Centralized	Increased inflow from the major canal caused by the Manaqil extension and increased water demand in the 1960s
SIM-8	Ad hoc	

Table 3.4: Summary of scenarios.

These scenarios investigate the claims on the causes of sedimentation due to different maintenance strategies and environmental conditions, incorporating the outputs of the previous sub-questions. Figure 2.2 shows the timeline of management and environmental factors that have been thought to impact sedimentation in the Gezira Scheme. The scenarios simulate the changes that are indicated in the timeline. For example, SIM-1 reflects the pre-independence situation between

1925 and 1956, when the Gezira Scheme was supposed to be operating according to Lacey's regime theory design. Between the 1960s and 2000s, an increased inflow due to the Manaqil Extension and higher water demand are represented by SIM-7. After the 2000s, erosion from upstream areas and the transition to ad hoc maintenance in 2005 are represented by SIM-4 and SIM-4.5. These scenarios were also simulated under different maintenance strategies to see its impact on sediment accumulation in Gezira's canals.

Main research question: How do different environmental conditions and maintenance strategies impact sediment deposition in the minor canals of the Gezira Irrigation Scheme?

The results of the GSAB Model scenarios suggest that sedimentation has been an issue since the Gezira Scheme opened in the 1920s. In the model, the baseline scenario simulations indicate that even with the intended canal design based on Lacey's regime theory method and centralized maintenance, 69% of the minor canals are still filled with sediment after 100 years. With ad hoc maintenance under design conditions, there is slightly less sediment left in the minor canals, approximately 67% of the full minor canal volume on average. The model's results present evidence that centralized maintenance does not perform as well as ad hoc maintenance regardless of the environmental condition. Of all the scenarios, erosion from upstream areas poses the largest threat to sedimentation in the Gezira canals. The sediment concentration drives the deposition mechanism in the GSAB Model which causes the minor canals to clog quickly. Centralized maintenance is insufficient for unclogging the canals, resulting in the highest sediment deposition rate compared to all the other scenarios (SIM-3). On the other hand, ad hoc maintenance can better mitigate the high sediment load because it is triggered before the canals become clogged. The results of the GSAB Model reflect the nature of each maintenance strategy; centralized maintenance is confined to the off-season period and occurs biennially while ad hoc maintenance can occur throughout the year in any given year. This allows ad hoc maintenance to be more adaptable to unfavorable environmental conditions. On the other hand, the schedule of centralized maintenance remains rigid, limiting its capacity for sediment removal. Additionally, a higher incoming water flow also increases the amount of sediment deposition in the model; in this case, ad hoc maintenance removes more sediment than centralized maintenance so that the canals are left with less net sediment deposition at the end of the simulation. Nevertheless, an increased flow rate does not worsen sediment deposition in the minor canals as much as a higher sediment load. Both centralized and ad hoc maintenance strategies still have the capacity to maintain a steady level of sediment removal with a higher water inflow in the GSAB Model.

Despite the lack of empirical measurements over time, ABM is a useful tool for reconstructing potential historical sediment trajectories. The results of the GSAB Model do not support the claim that the management change from centralized to tenant-run maintenance was the main contributing factor to worsening sedimentation in the Gezira Scheme. Instead, the GSAB Model presents evidence that the original design of the canals already had crucial drawbacks, and centralized maintenance even during colonial times did not have adequate capacity to mitigate it. By the time tenants inherited O&M responsibilities in 2005, it is likely that upstream erosion, increased water discharge, and insufficient centralized maintenance had already caused the canals to be clogged with sediment. Tenants likely inherited a canal system with excessive sediment, making it tough for them to desilt effectively. In addition, sediment concentration was found to be the dominating environmental cause of sedimentation in the Gezira canals. Given that the sediment in Gezira is fine and exhibits cohesive sediment transport, sediment deposition is highly driven by the sediment concentration. Especially under unideal environmental conditions, selecting an appropriate maintenance strategy is crucial as it can either mitigate or worsen sedimentation in the canals.

Chapter 7

Reflection

In 2020, O&M responsibilities were transferred back to the Sudanese government from the WUAs. Based on the results of the GSAB Model, it is recommended that management address several operational aspects of the canals to reduce sedimentation today. First, the canal design should be refined. Environmental factors and overdredging have changed the profile of the canals over time; therefore, they no longer function like the non-scouring regime theory canals they were designed to be. The canal design should be adjusted so that any additional sediment are more easily kept in suspension, thereby preventing sediment deposition in the canals.

Second, the weir control structures should be checked to ensure that they are functioning properly. While increasing the maintenance capacity will no doubt impede sediment accumulation in the minor canals, it is more effective to ensure that control structures prevent excessive sediment from entering in the first place. Installing a monitoring system on the control structures can help detect any functional deterioration early so that they can be fixed quickly.

Third, the incoming sediment load should be reduced by curbing erosion from upstream areas. Implementing upstream sediment detention reservoirs and introducing additional soil conservation practices can help decrease the sediment load. For example, better management of agriculture and livestock grazing can forestall soil loss from erosion. These interventions could lessen the sediment concentration of water entering the Gezira Scheme. However, they require a high resource commitment and transnational collaboration.

Finally, maintenance operations should not be confined to a particular maintenance period but rather be based on the available water supply. Adjusting desilting efforts to start as soon as the water supply is restricted allows more sediment to be removed over time. In addition, this method provides flexibility to address sedimentation under unfavorable and changing environmental conditions before the canals become clogged. A monitoring system for the Gezira canals is needed so that the sediment depth and water level can be measured and recorded. Doing so would allow management to acquire systematic data collection over time and detect sedimentation in the canals as soon as it occurs.

References

Ahmed, A. A. (2009). Gezira Scheme Irrigation System Performance after 80 years of Operation. *International Conference on Water, Environment, Energy, and Society.*

Ahmed, A. A., & Ismail, U. H. A. E. (2008). Sediment in the Nile River system. *Consultancy Study requested by UNESCO.*

Ali, A. M., Osman, I. S., Khalid, H., Albager, M., & Ibrahim, A. (2021). The Impact of Different Design Approaches on Fine Sediment Transport in Gezira Scheme, Sudan. *Water resources in arid lands: Management and sustainability* (pp. 55–72). Springer.

Ali, M. (2020). The Canals Never Lie: MASSCOTE framework and modeling of operation strategies in the Gezira Irrigation Scheme.

Ali, Y. S. A. (2014). *The impact of soil erosion in the upper blue nile on downstream reservoir sedimentation.* Citeseer.

Balthazar, V., Vanacker, V., Girma, A., Poesen, J., & Golla, S. (2013). Human impact on sediment fluxes within the Blue Nile and Atbara River basins. *Geomorphology*, *180*, 231–241.

Barr, D., Herbertson, J., Blench, T., Neill, C., Kramer, A., Smith, K., Komura, S., McDowell, D., Prus Chacinski, T., Bogardi, J., et al. (1970). Discussion. a Similitude Framework of Regime Theory. *Proceedings of the Institution of Civil Engineers*, *45*(2), 285–328.

Bernal, V. (1990). The politics of research on agricultural development: An instructive example from the Sudan. *American anthropologist*, *92*(3), 732–739.

Carlin, G. D., Cook, F., Cropp, R., Hartcher, M., Smajgl, A., Yu, B., & Heckbert, S. (2007). Using a catchment contour approach for simulating ground and surface water behaviour within agent-based modelling platforms. *ModSim2007.*

Cossart, E., Viel, V., Lissak, C., Reulier, R., Fressard, M., & Delahaye, D. (2018). How might sediment connectivity change in space and time? *Land Degradation & Development*, *29*(8), 2595–2613.

Cunge, J. (1980). Practical aspects of computational river hydraulics. *Pitman Publishing Ltd. London,(17 CUN), 1980, 420.*

Davies, B., Holdaway, S. J., & Fanning, P. C. (2016). Modelling the palimpsest: An exploratory agent-based model of surface archaeological deposit formation in a fluvial arid Australian landscape. *The Holocene*, *26*(3), 450–463.

Depeweg, H., & Méndez, N. (2002). Sediment transport applications in irrigation canals. *Irrigation and Drainage: The journal of the International Commission on Irrigation and Drainage*, *51*(2), 167–179.

Depeweg, H., & Méndez, N. (2007). *A New Approach to Sediment Transport in the Design and Operation of Irrigation Canals: UNESCO-IHE Lecture Note Series*. CRC Press.

El Monshid, B., El Awad, O., & Ahmed, S. (1997). Environmental effect of the Blue Nile Sediment on the reservoirs and irrigation canals. 5th Nile 2002 Conference. *Addis Ababa*.

Eldaw, A. M. (2004). The Gezira Scheme: Perspectives for sustainable development. *German Development Institute*.

Elhassan, M., & Ahmed, E. (2008). Watershed degradation and its impacts on agricultural area and crop production in Gezira Scheme. *Nile Basin Development Forum, Friendship Hall Khartoum, Sudan*, 17–19.

Erasmus, C. J. (1956). Culture structure and process: The occurrence and disappearance of reciprocal farm labor. *Southwestern journal of anthropology*, *12*(4), 444–469.

Ertsen, M. W. (2016a). *Improvising planned development on the Gezira Plain, Sudan, 1900-1980*. Springer.

Ertsen, M. W. (2016b). A Matter of Relationships: Actor Networks of Colonial Rule in the Gezira Irrigation System, Sudan. *Water Alternatives*, *9*(2).

Giri, S., Arbab, N. N., & Lathrop, R. G. (2019). Assessing the potential impacts of climate and land use change on water fluxes and sediment transport in a loosely coupled system. *Journal of Hydrology*, *577*, 123955.

Gismalla, Y. A. (2009). Sedimentation problems in the Blue Nile Reservoirs and Gezira scheme. *Gezira Journal of Engineering and Applied Sciences*, *4*(2), 1–19.

Gismalla, Y. A. (2018). Sediment Balance in the Blue Nile in Sudan. *Gezira Journal of Engineering and Applied Sciences*, *9*(2).

Goelnitz, A., & Al-Saidi, M. (2020). Too big to handle, too important to abandon: Reforming Sudan's Gezira scheme. *Agricultural Water Management*, *241*, 106396.

Gould, S. J. (1990). *Wonderful life: The Burgess Shale and the nature of history*. WW Norton & Company.

Hooke, J. (2003). Coarse sediment connectivity in river channel systems: A conceptual framework and methodology. *Geomorphology*, *56*(1-2), 79–94.

Johnstone, H. V. C. (1929). The Gezira Irrigation Scheme: Canalization of the Gezira. *Minutes of the Proceedings of the Institution of Civil Engineers*, *227*(1929), 68–94.

Kabora, T., Stump, D., & Wainwright, J. (2020). How did that get there? Understanding sediment transport and accumulation rates in agricultural landscapes using the ESTTraP agent-based model. *Journal of Archaeological Science: Reports*, *29*, 102115.

Krone, R. (1962). Flume studies of the transport of sediment in estuarial shoaling processes. Final Report, Hydraulic Eng. *Lab. and Sanitary Eng. Res. Lab., University of California, Berkeley*, 110.

Lacey, G. (1930). Stable Channels in Alluvium. *Minutes of the Proceedings of the Institution of Civil Engineers*, *229*(1930), 259–292.

Lawrence, P., & Atkinson, E. (1998). Deposition of fine sediments in irrigation canals. *Irrigation and Drainage Systems*, *12*(4), 371–385.

Lesschen, J. P., Schoorl, J. M., & Cammeraat, L. (2009). Modelling runoff and erosion for a semi-arid catchment using a multi-scale approach based on hydrological connectivity. *Geomorphology*, *109*(3-4), 174–183.

Lumborg, U. (2005). Modelling the deposition, erosion, and flux of cohesive sediment through Øresund. *Journal of Marine Systems*, *56*(1-2), 179–193.

Mabry, J. B. (Ed.). (2008). Las Capas: Early Irrigation and Sedentism in a Southwestern Floodplain. *Archaeology Southwest, Anthropological papers*, (28).

Majumdar, S., Shukla, S., & Maiti, A. (2018). Open Agent-based Runoff and Erosion Simulation (OARES): A Generic Cross Platform Tool for Spatio-temporal Watershed Monitoring Using Climate Forecast System Reanalysis Weather Data. *ISPRS Annals of Photogrammetry, Remote Sensing & Spatial Information Sciences*, *4*(4).

Mamad, N. (2010). *Irrigation performance of Gezira scheme, Sudan: Assessment of land and water productivity using satellite data* (Doctoral dissertation). UNESCO-IHE.

Matthews, I. S. G. (1952). *Investigation of Stable Channels in the Gezira Canalisation Scheme* (SID, Tech. Note No. 3/52).

Mendez, N. J. (1998). *Sediment transport in irrigation canals* (Doctoral dissertation). Wageningen Agricultural University.

Ministry of Irrigation and Hydro-Power, Sudan. (1934). *Gezira Canal Regulation Handbook.*

Mouri, G., Ros, F. C., & Chalov, S. (2014). Characteristics of suspended sediment and river discharge during the beginning of snowmelt in volcanically active mountainous environments. *Geomorphology*, *213*, 266–276.

Müller, B., Bohn, F., Dreßler, G., Groeneveld, J., Klassert, C., Martin, R., Schlüter, M., Schulze, J., Weise, H., & Schwarz, N. (2013). Describing human decisions in agent-based models–ODD+D, an extension of the ODD protocol. *Environmental Modelling & Software*, *48*, 37–48.

Osman, I. S. (2015). Impact of improved operation and maintenance on cohesive sediment transport in Gezira Scheme, Sudan.

Osman, I. S., Schultz, B., Osman, A., & Suryadi, F. (2016). Simulation of fine sediment transport in irrigation canals of the Gezira scheme with the numerical model FSEDT. *Journal of Irrigation and Drainage Engineering*, *142*(11).

Osman, I. S., Schultz, B., Osman, A., & Suryadi, F. (2017). Effects of different operation scenarios on sedimentation in irrigation canals of the Gezira Scheme, Sudan. *Irrigation and Drainage*, *66*(1), 82–89.

Partheniades, E. (1965). Erosion and deposition of cohesive soils. *Journal of the Hydraulics Division*, *91*(1), 105–139.

Partheniades, E. (2009). *Cohesive sediments in open channels: Erosion, transport and deposition*. Butterworth-Heinemann.

Plusquellec, H. (1990). The Gezira irrigation scheme in Sudan. *World Bank Technical Paper*, *120*.

Romanowska, I., Wren, C. D., & Crabtree, S. A. (2021). *Agent-Based Modeling for Archaeology: Simulating the Complexity of Societies*. SFI Press.

Schneider, A. (2019). *GPS Visualizer*. Retrieved February 23, 2022, from https://www.gpsvisualizer.com/elevation

Setegn, S. G., Srinivasan, R., Dargahi, B., & Melesse, A. M. (2009). Spatial delineation of soil erosion vulnerability in the Lake Tana Basin, Ethiopia. *Hydrological Processes: An International Journal*, *23*(26), 3738–3750.

Shrestha, A., Ezee, G., Adhikary, R., Rai, S., et al. (2012). *Resource manual on flash flood risk management. Module 3: Structural measures*. International Centre for Integrated Mountain Development (ICIMOD).

Simons, D. B., & Şentürk, F. (1992). *Sediment transport technology: Water and sediment dynamics*. Water Resources Publication.

Stevens, M. A., & Nordin Jr, C. F. (1987). Critique of the regime theory for alluvial channels. *Journal of Hydraulic Engineering*, *113*(11), 1359–1380.

Theol, S. A., Jagers, B., Suryadi, F., & De Fraiture, C. (2019). The role of gate operation in reducing problems with cohesive and non-cohesive sediments in irrigation canals. *Water*, *11*(12), 2572.

US Army Corp of Engineers. (2022). *Tractive Force Method*. Retrieved May 4, 2022, from https://www.hec.usace.army.mil/confluence/rasdocs/ras1dtechref/latest/stable-channel-design-functions/stable-channel-design/tractive-force-method#:~:text=Essentially%5C%20an%5C%20analytical%5C%20stable%5C%20design,when%5C%20two%5C%20others%5C%20are%5C%20given.

Van Dam, K. H., Nikolic, I., & Lukszo, Z. (2012). *Agent-based modeling of socio-technical systems* (Vol. 9). Springer Science & Business Media.

Wallingford, H. (1990). Siltation monitoring study. *Research for Rehabilitation EX*, *2244*.

Whitehouse, R. J. S., Soulsby, R. L., Roberts, W., & Mitchener, H. J. (2000). *Dynamics of estuarine muds*. Thomas Telford.

Willensky, U. (2021). *Netlogo*. https://ccl.northwestern.edu/netlogo/ Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.

Winterwerp, J. C., Van Kessel, T., van Maren, D. S., & Van Prooijen, B. C. (2022). *Fine Sediment in Open Water: From Fundamentals to Modeling*. World Scientific.

Winterwerp, J. C., & Van Kesteren, W. G. M. (2004). *Introduction to the physics of cohesive sediment dynamics in the marine environment*. Elsevier.

Woldegebriel, E. (2011a). *Irrigation management transfer in the Gezira Scheme, Sudan: A case study on farmers' operation and maintenance strategies in Tuweir minor canal* (Doctoral dissertation). Master Thesis Wageningen University.

Woldegebriel, E. (2011b). *Irrigation management transfer in the Gezira Scheme, Sudan: A case study on farmers' operation and maintenance strategies in Tuweir minor canal* (Doctoral dissertation). Master Thesis Wageningen University. Accessed on 21/3/2014 from: http://edepot.wur.nl/167523.

Woodson, M. K. (2010). *The social organization of hohokam irrigation in the middle Gila River valley, Arizona*. Arizona State University.

World Bank and Government of Sudan. (2000). Options for the Sustainable Development of the Gezira Scheme.

Appendix A

Appendix

A.1 Sensitivity of the Sediment Budget with Varying Central Maintenance Capacity

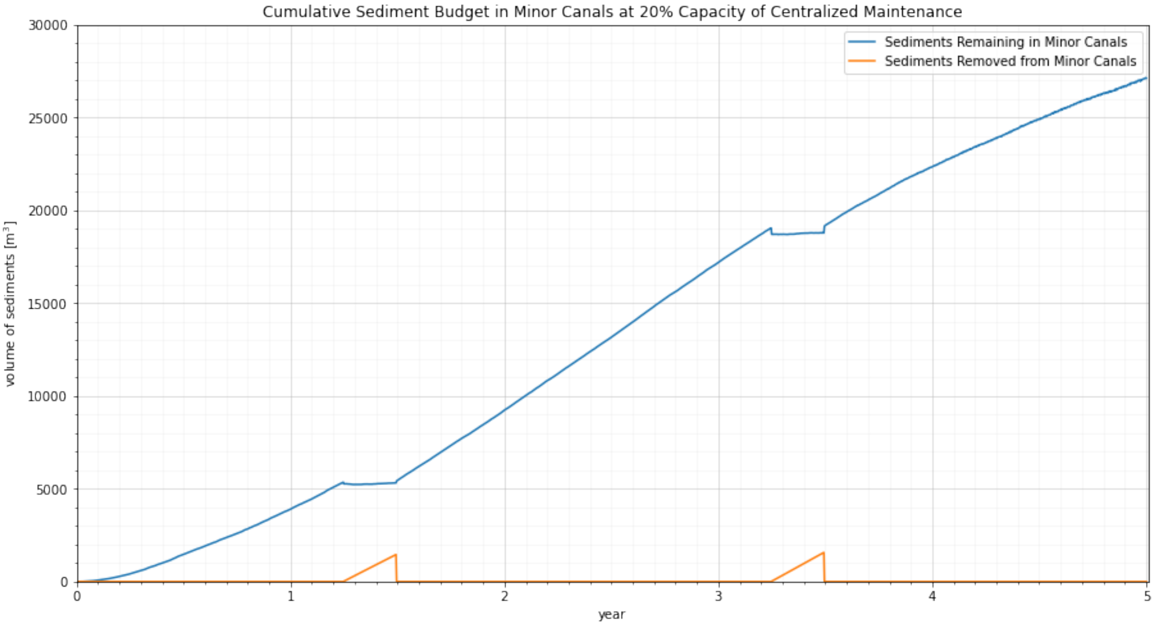


Figure A.1: Cumulative sediment deposition & removal with cap_c=20%.

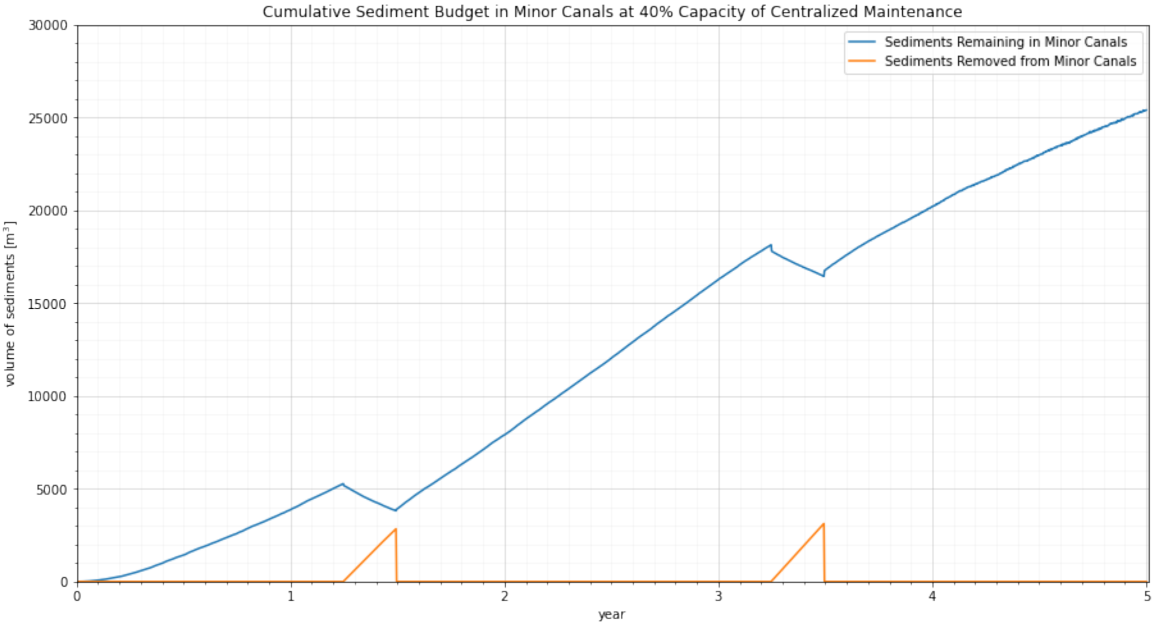


Figure A.2: Cumulative sediment deposition & removal with cap_c=40%.

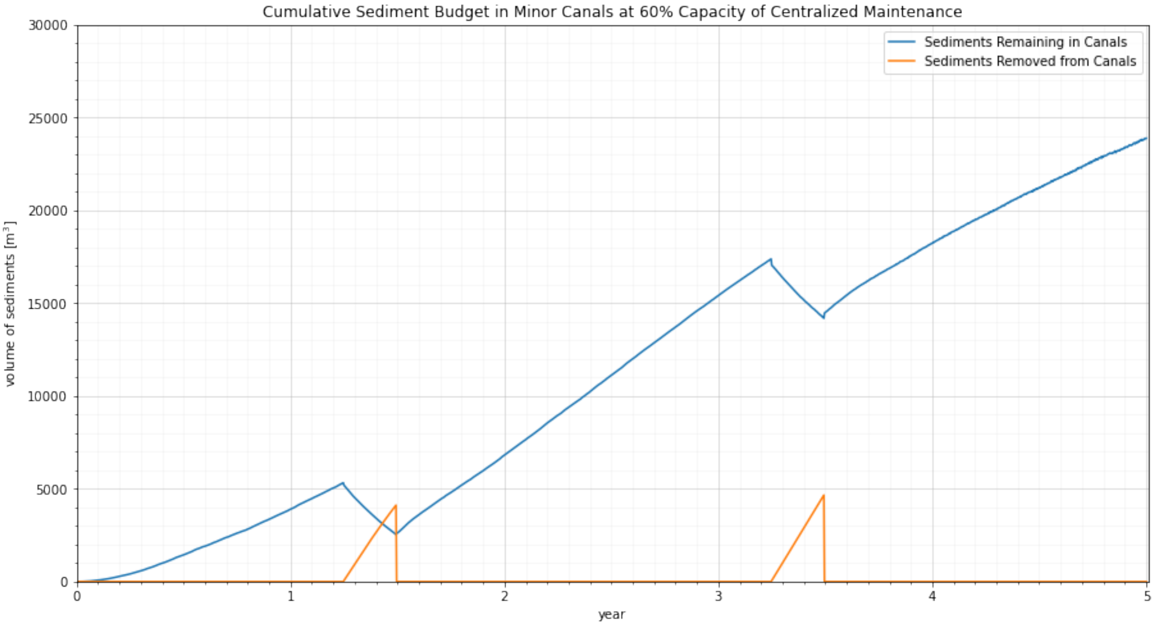


Figure A.3: Cumulative sediment deposition & removal with cap_c=60%.

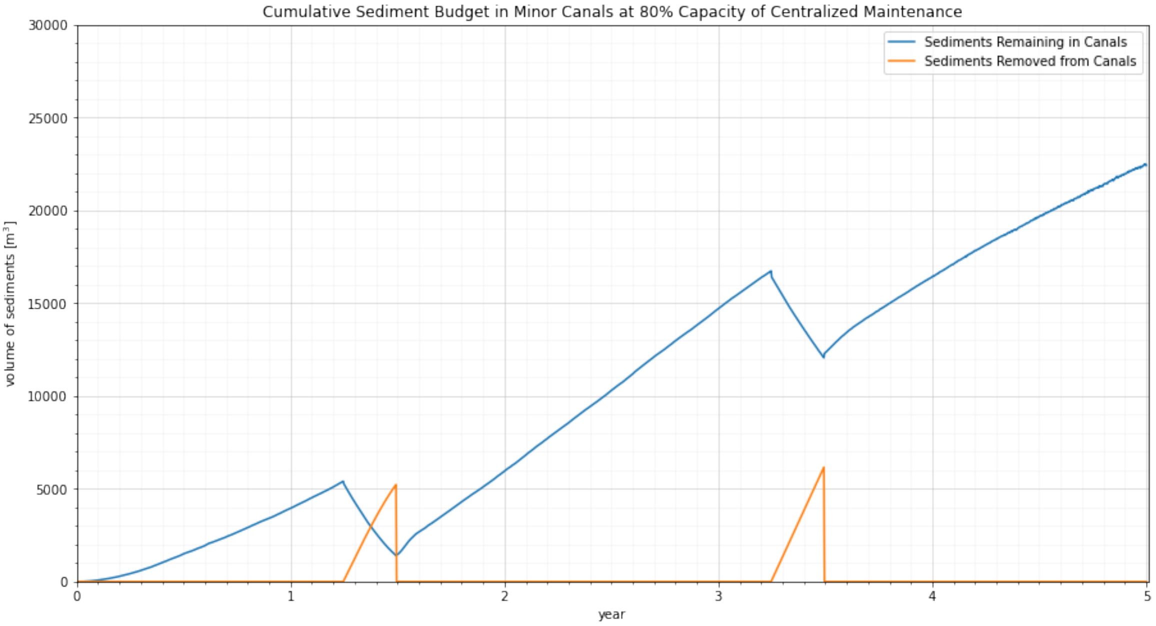


Figure A.4: Cumulative sediment deposition & removal with cap_c=80%.

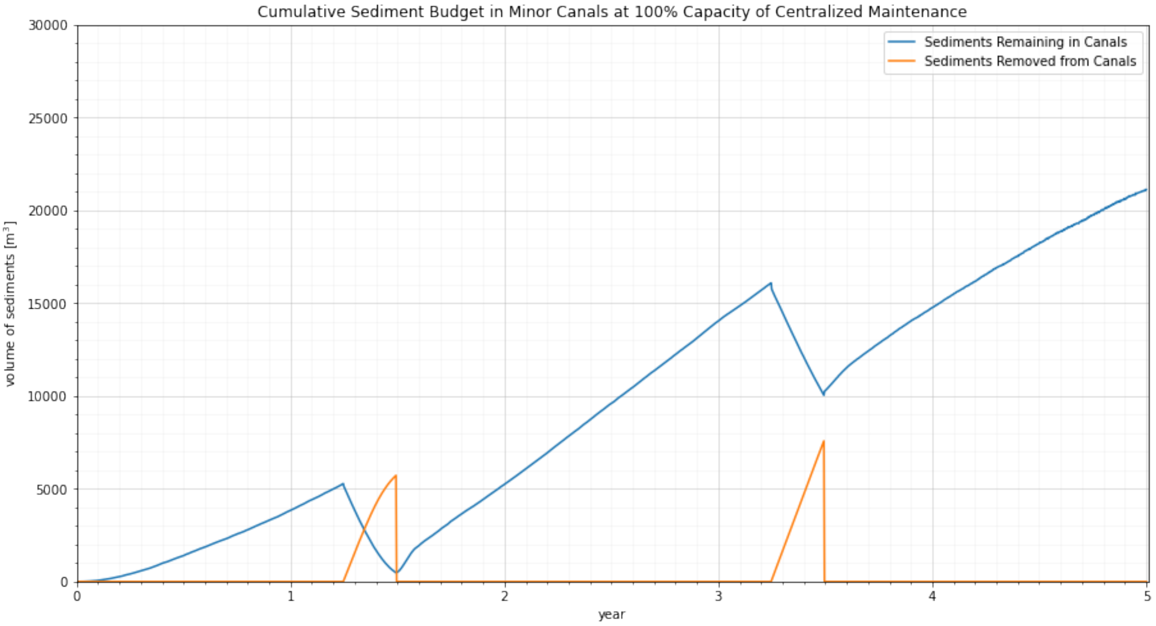


Figure A.5: Cumulative sediment deposition & removal with cap_c=100%.

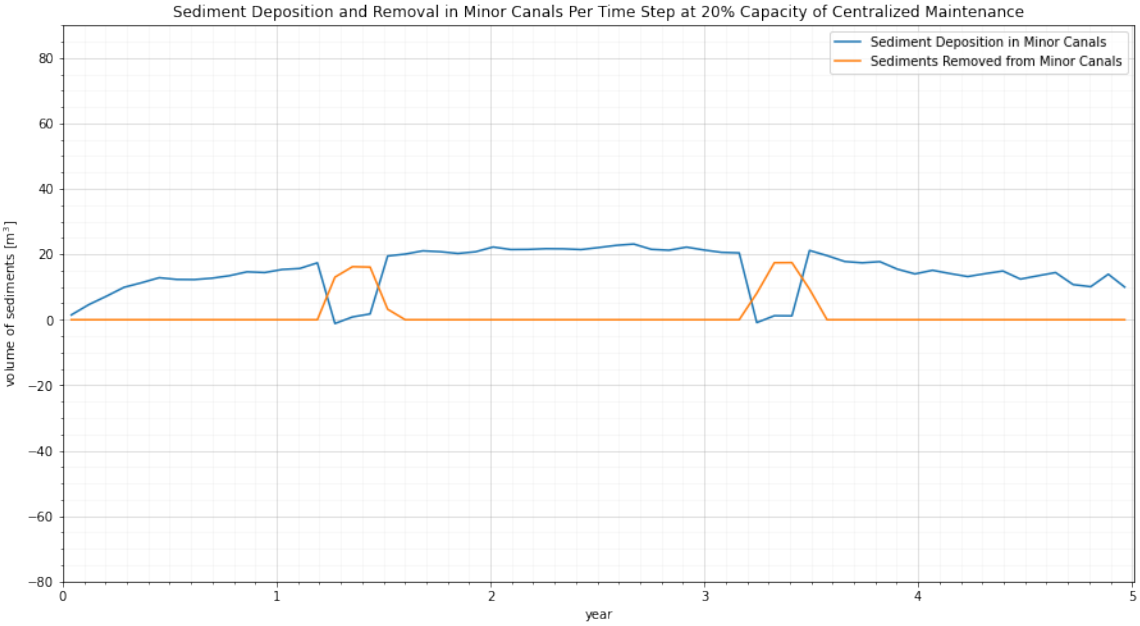


Figure A.6: Change in sediment deposition & removal with cap_c=20%.

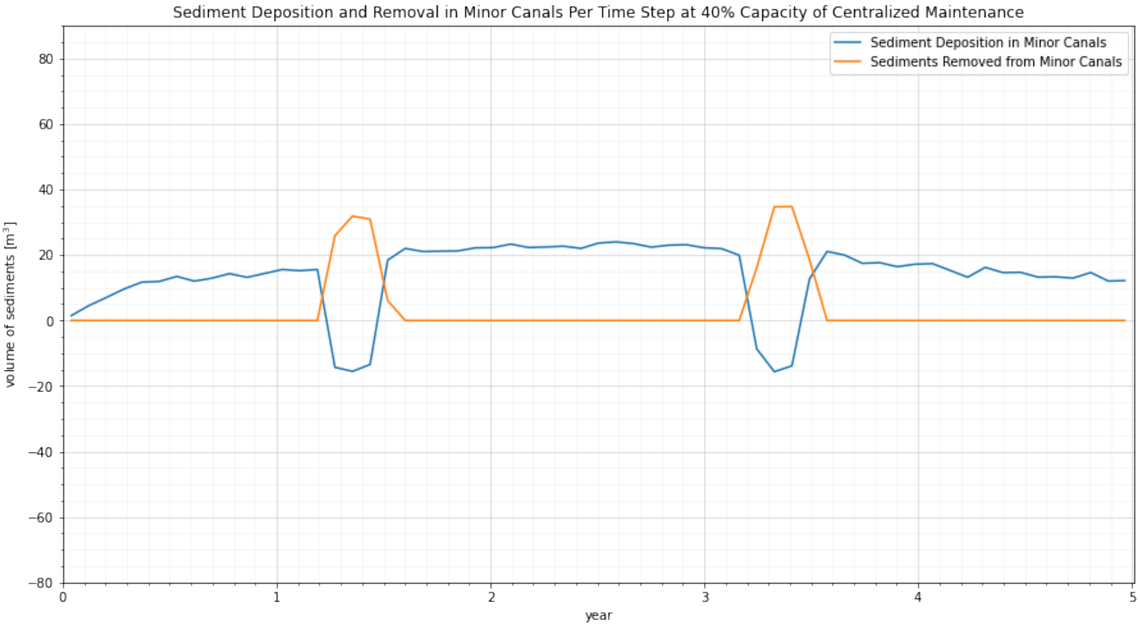


Figure A.7: Change in sediment deposition & removal with cap_c=40%.

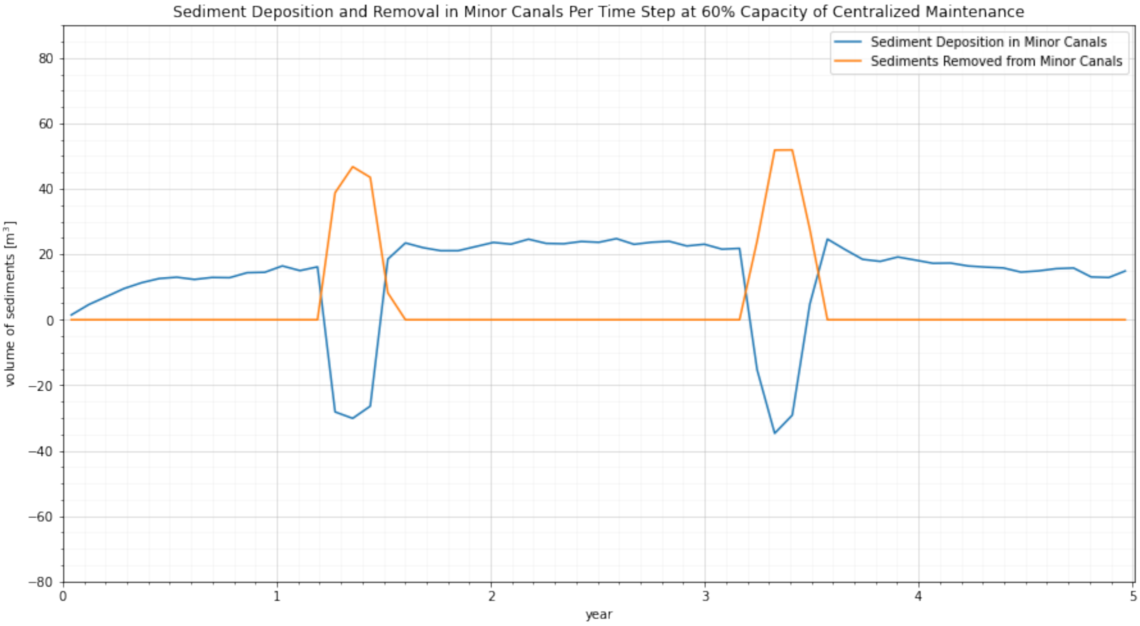


Figure A.8: Change in sediment deposition & removal with cap_c=60%.

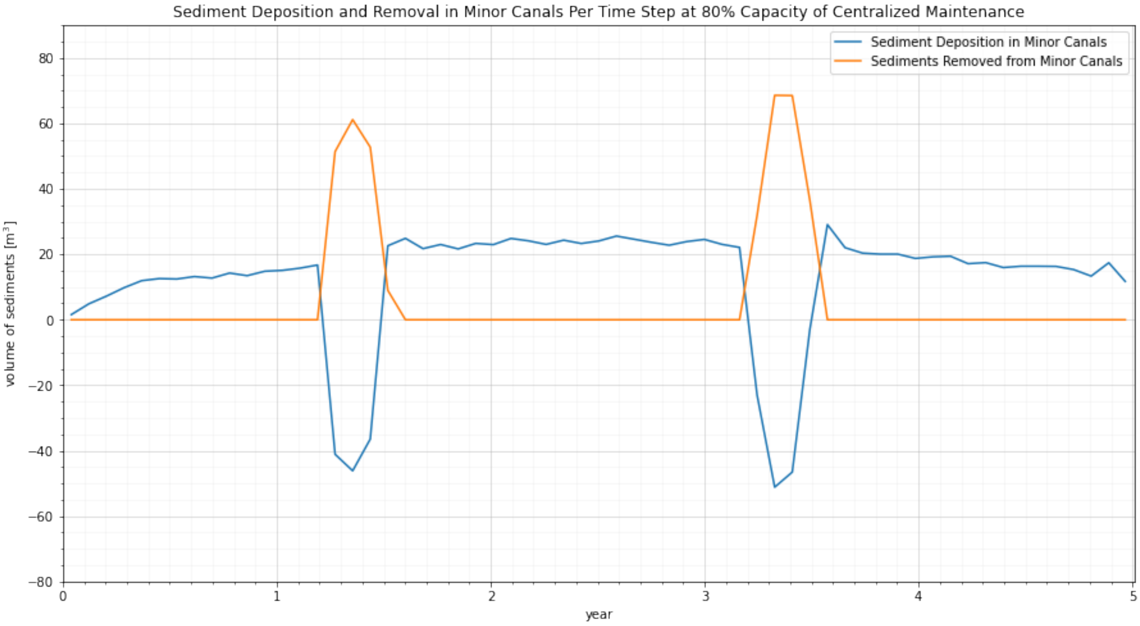


Figure A.9: Change in sediment deposition & removal with cap_c=80%.

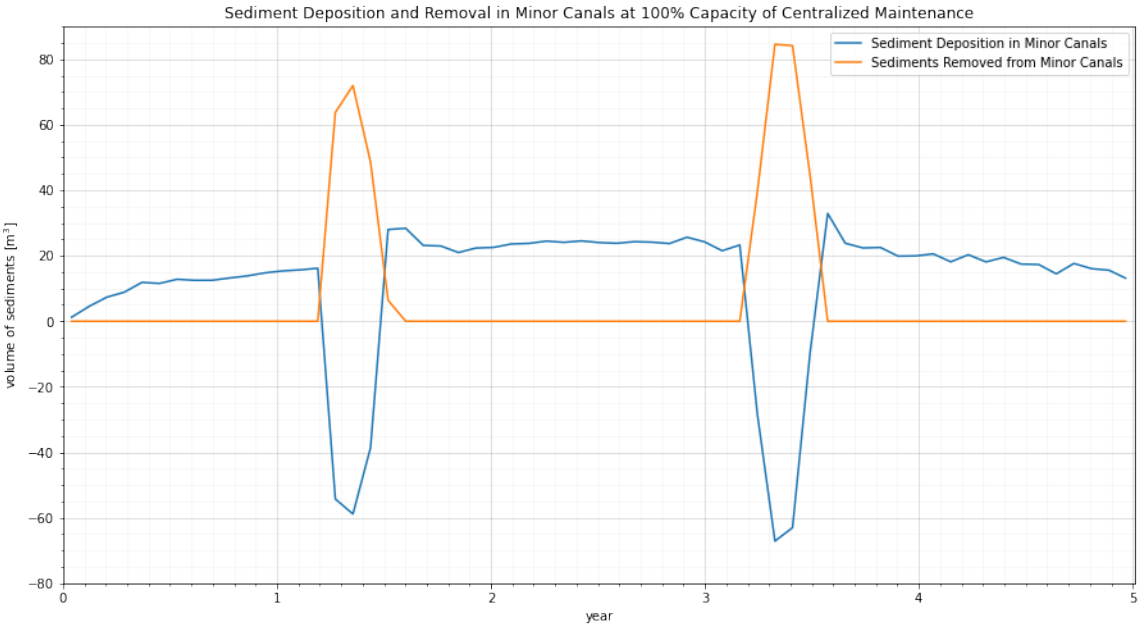


Figure A.10: Change in sediment deposition & removal with cap_c=100%.

A.2 Sensitivity of the Sediment Budget with Varying Ad hoc Maintenance Capacity

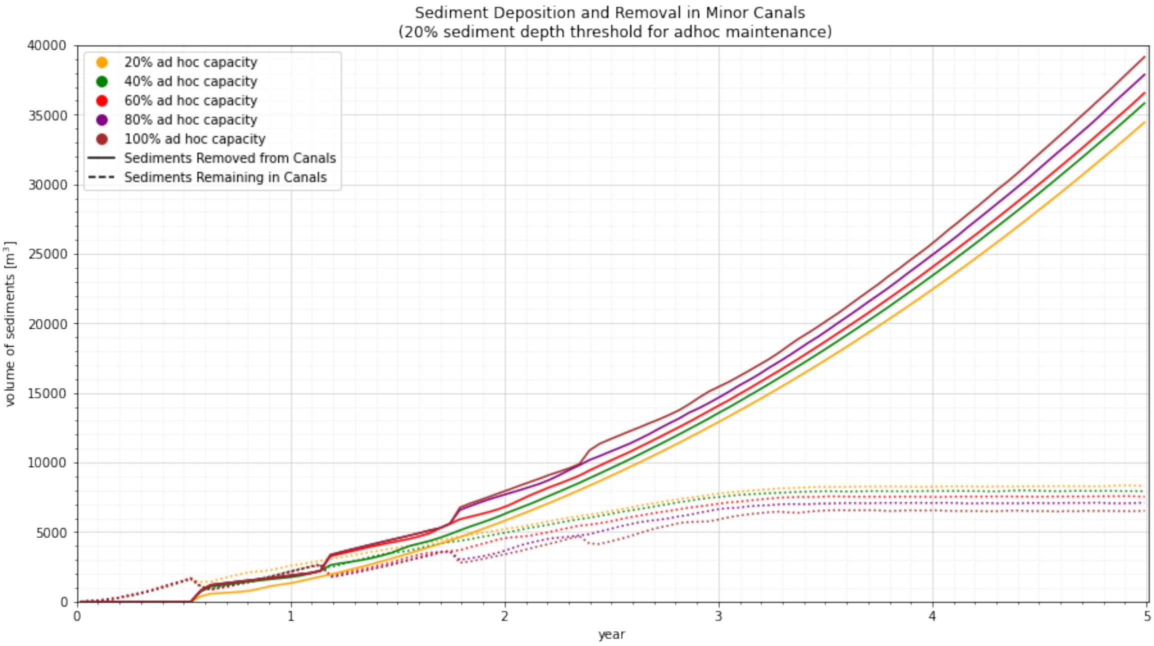


Figure A.11: Cumulative sediment deposition & removal with $h_{s,\%}$=20%.

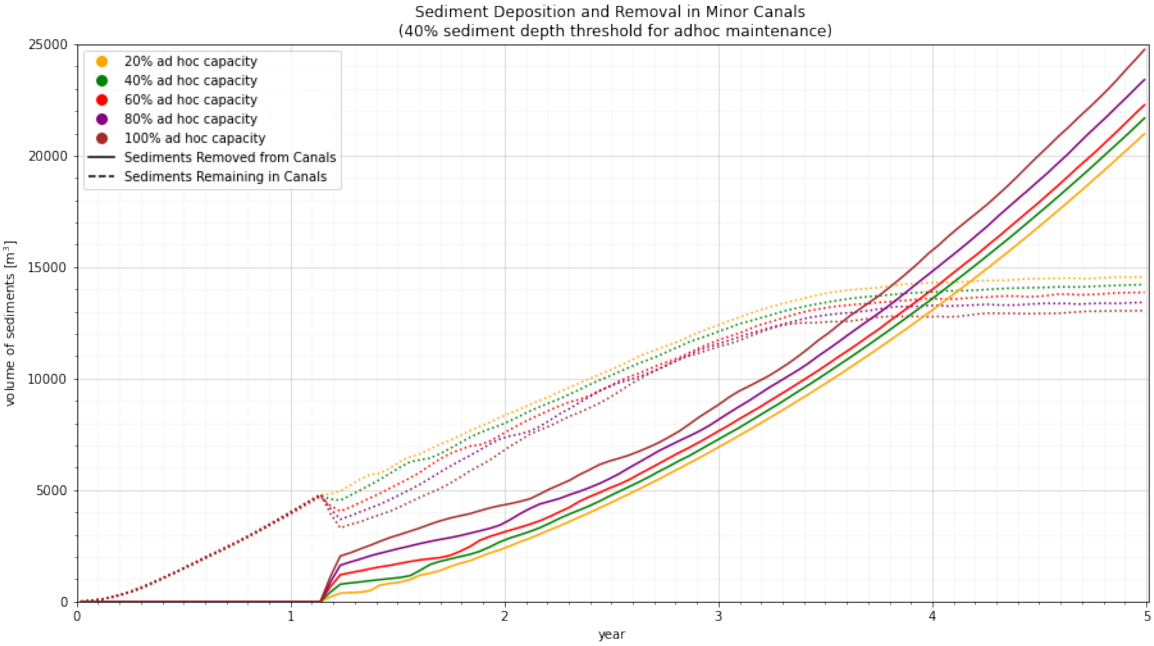


Figure A.12: Cumulative sediment deposition & removal with $h_{s,\%}$=40%.

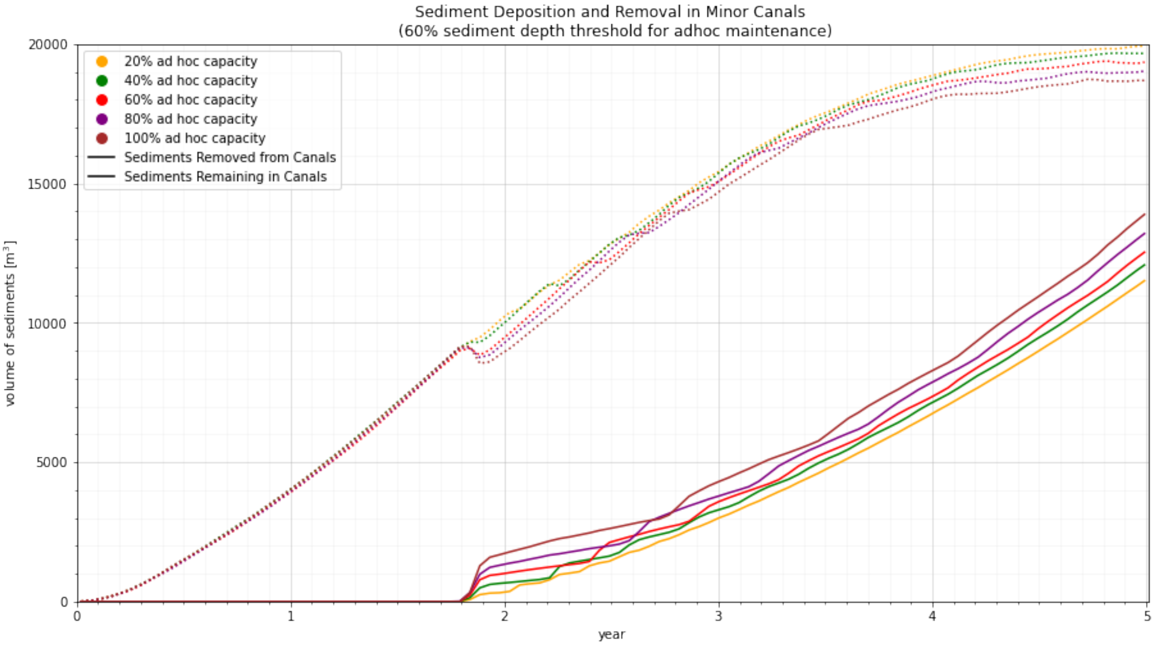


Figure A.13: Cumulative sediment deposition & removal with $h_{s,\%}$=60%.

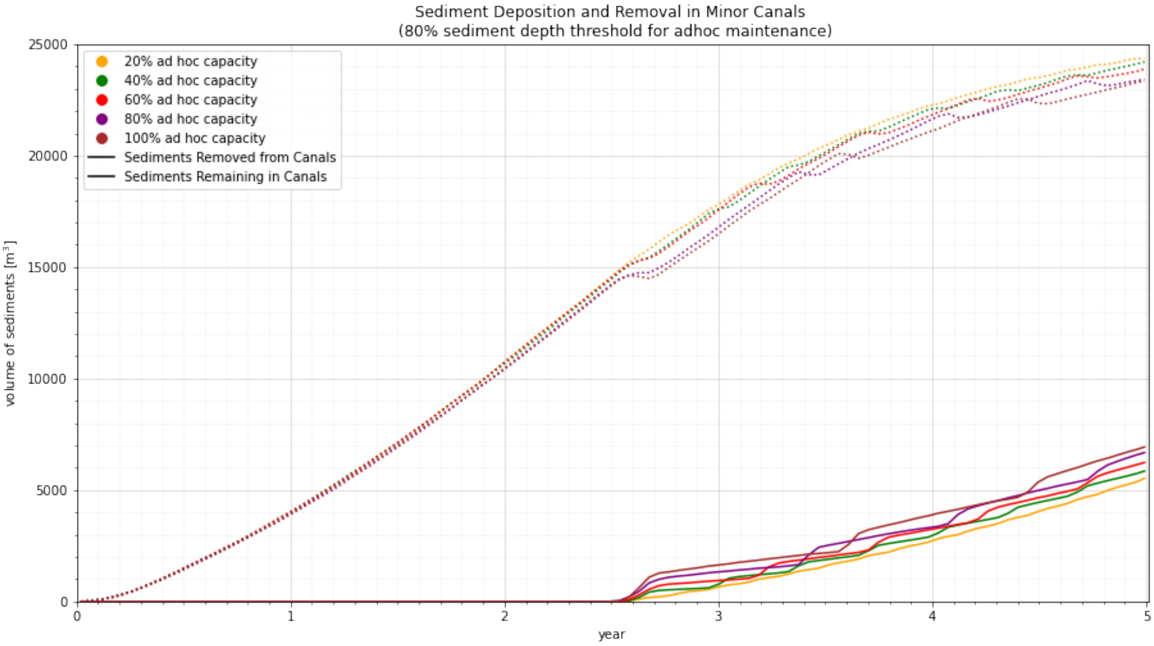


Figure A.14: Cumulative sediment deposition & removal with $h_{s,\%}$=80%.

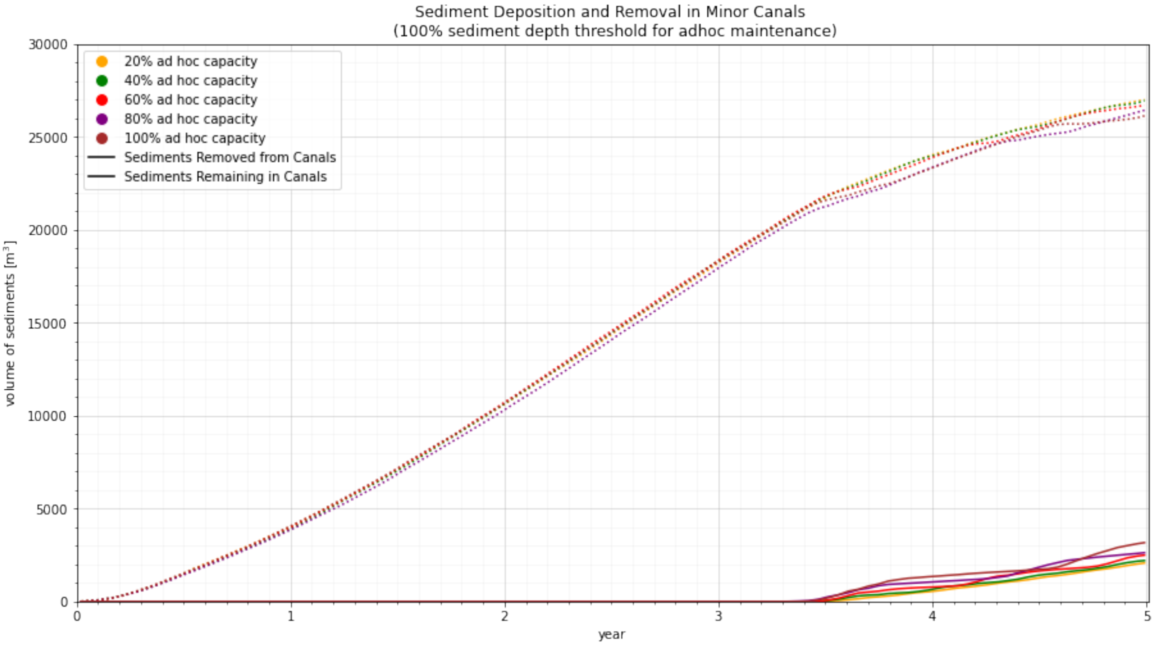
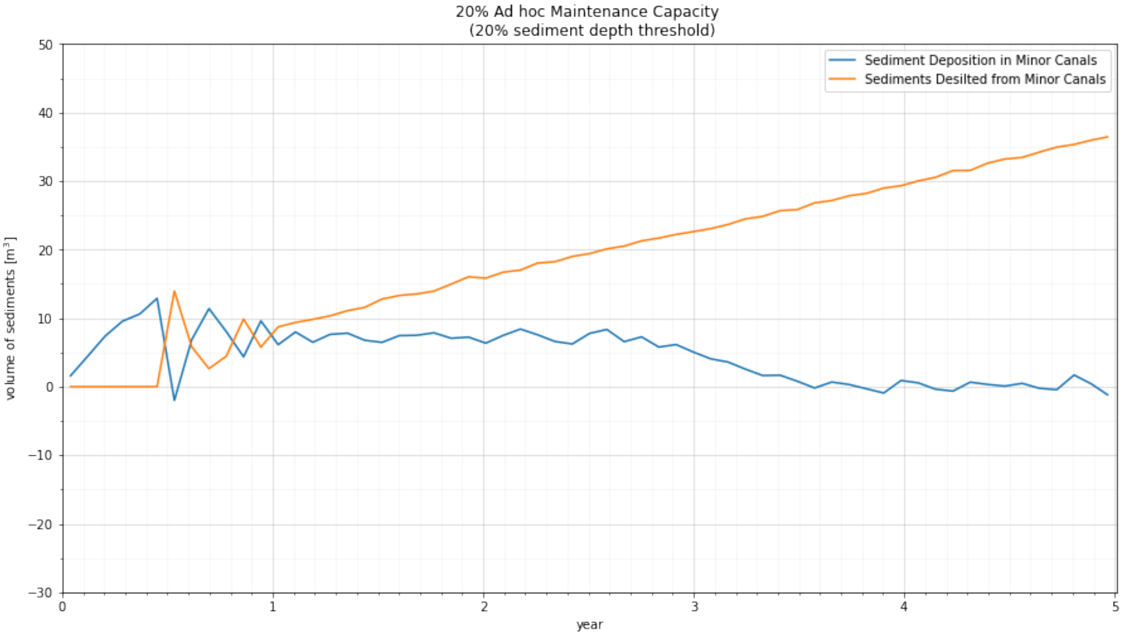
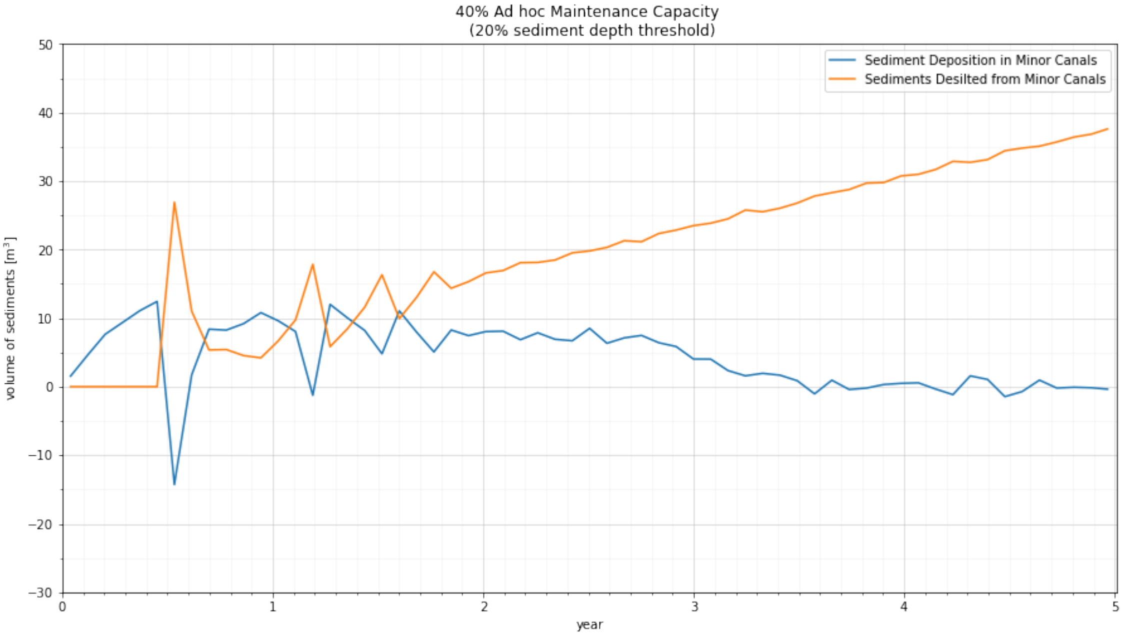


Figure A.15: Cumulative sediment deposition & removal with $h_{s,\%}$=100%.

The high peaks in Figures A.16 to A.20 show the points at which the sediment depth threshold is reached. The variation in the change in sediment accumulation in the minor canals reflect the resuspension, transport, and deposition of sediments within the minor canal along with additional sediment inflow from the Major canal.

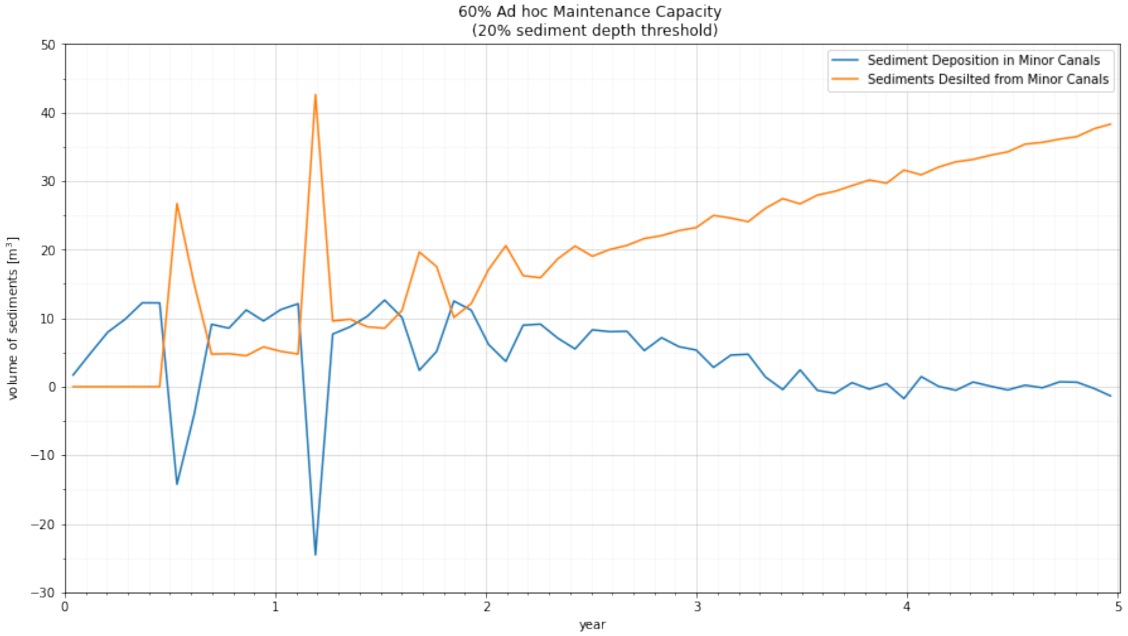


(a) 20% ad hoc maintenance capacity.

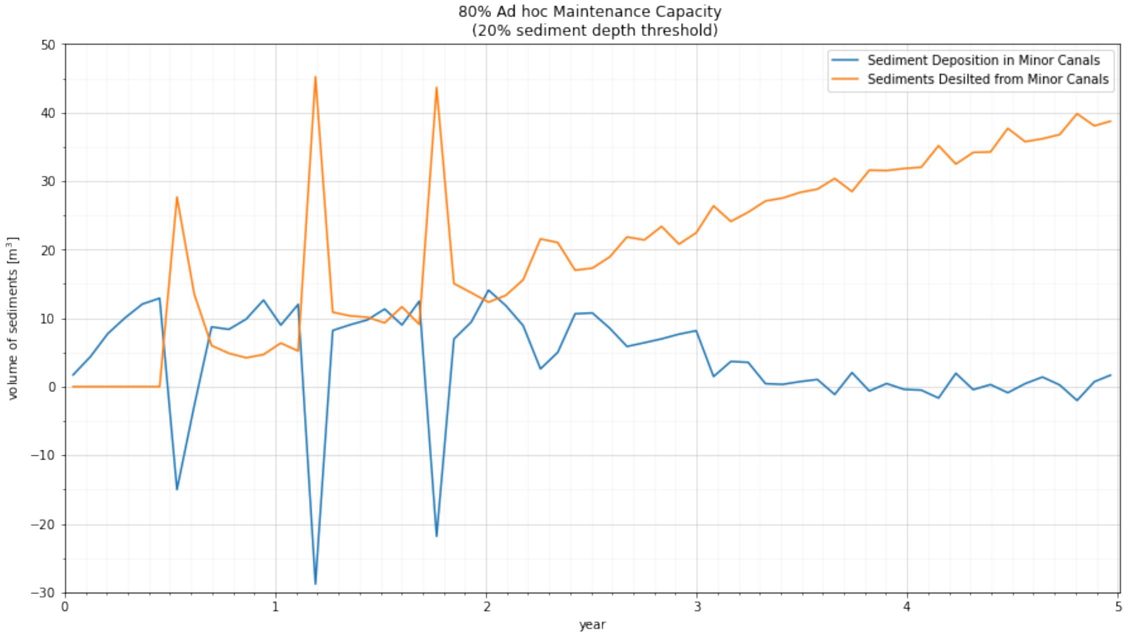


(b) 40% ad hoc maintenance capacity.

Figure A.16: Change in sediment deposition & removal at varying cap_a & $h_{s,\%}$=20%.

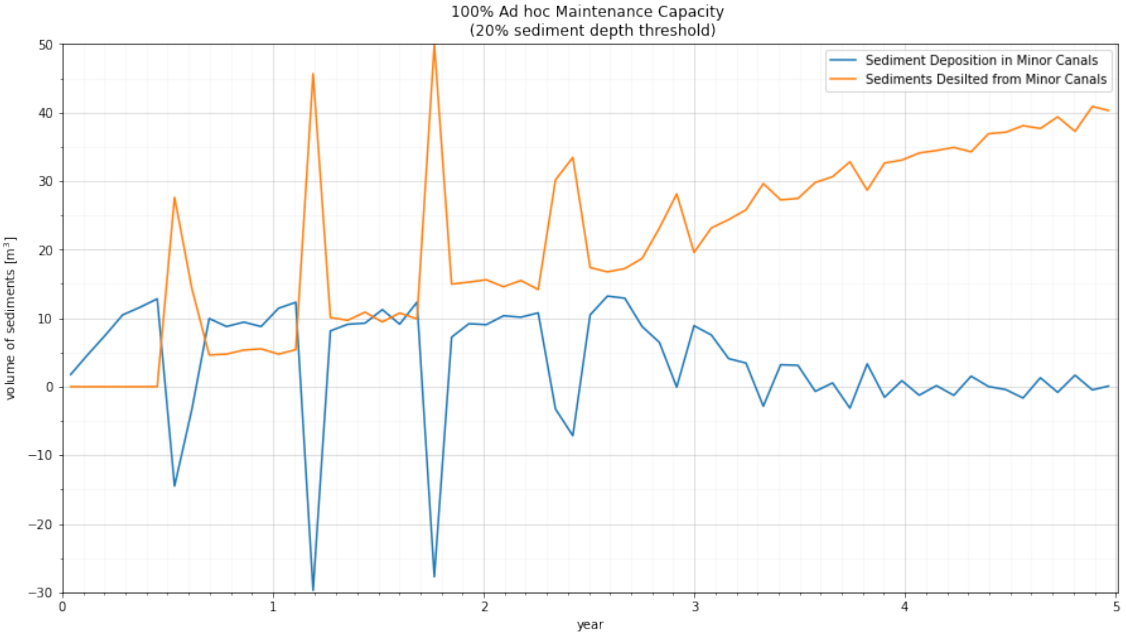


(c) 60% ad hoc maintenance capacity.



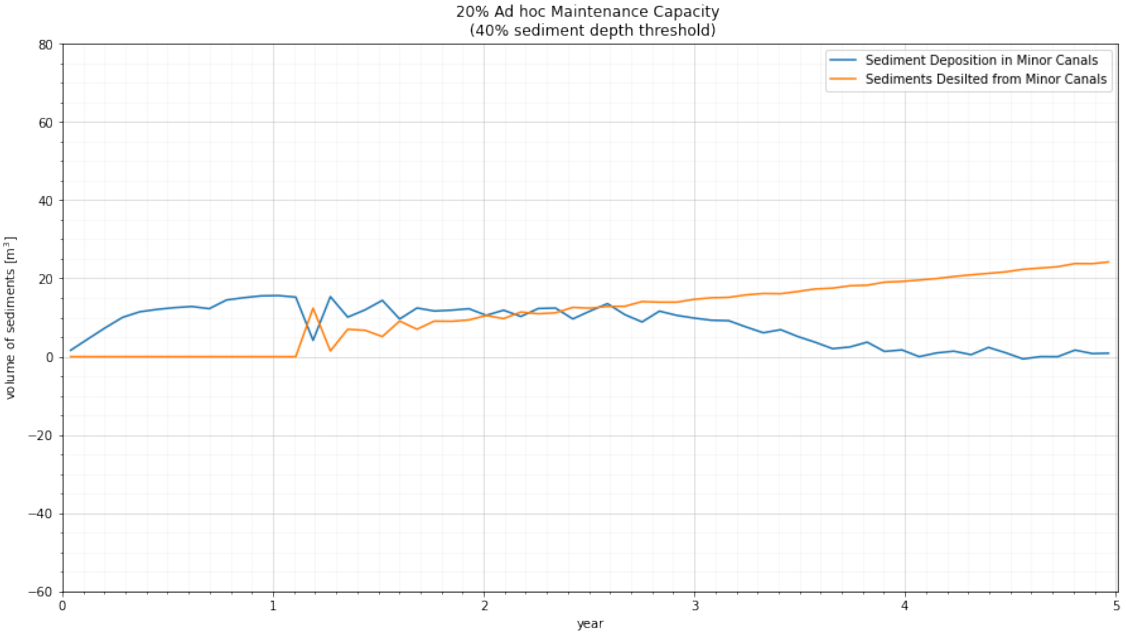
(d) 80% ad hoc maintenance capacity.

Figure A.16: Change in sediment deposition & removal at varying cap_a & $h_{s,\%}$=20% (continued).



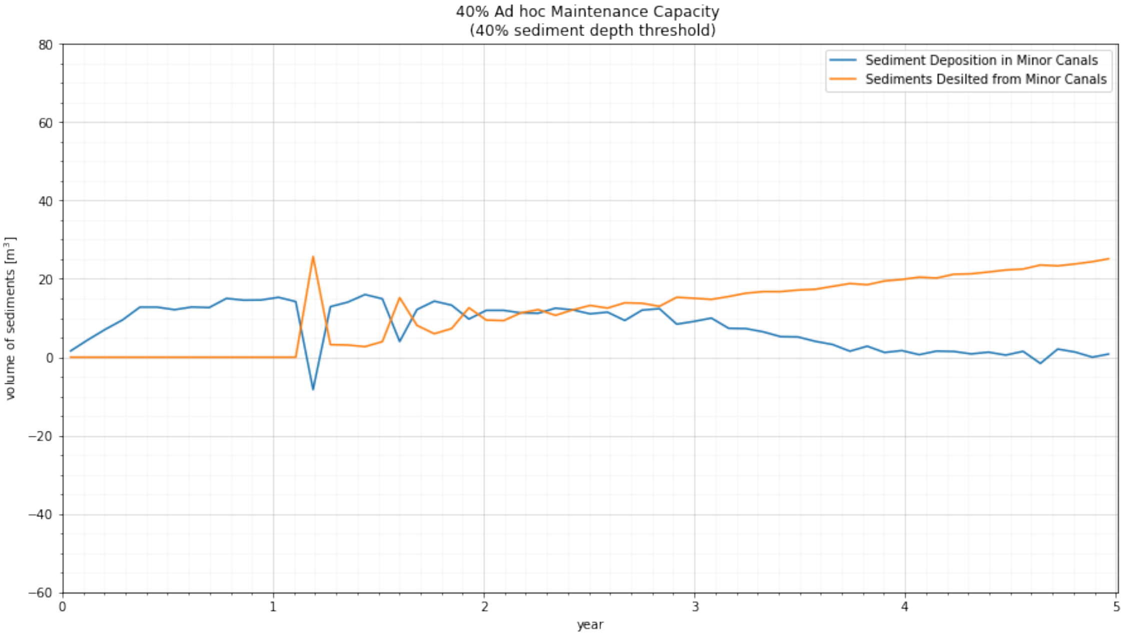
(e) 100% ad hoc maintenance capacity.

Figure A.16: Change in sediment deposition & removal at varying cap_a & $h_{s,\%}$=20% (continued).

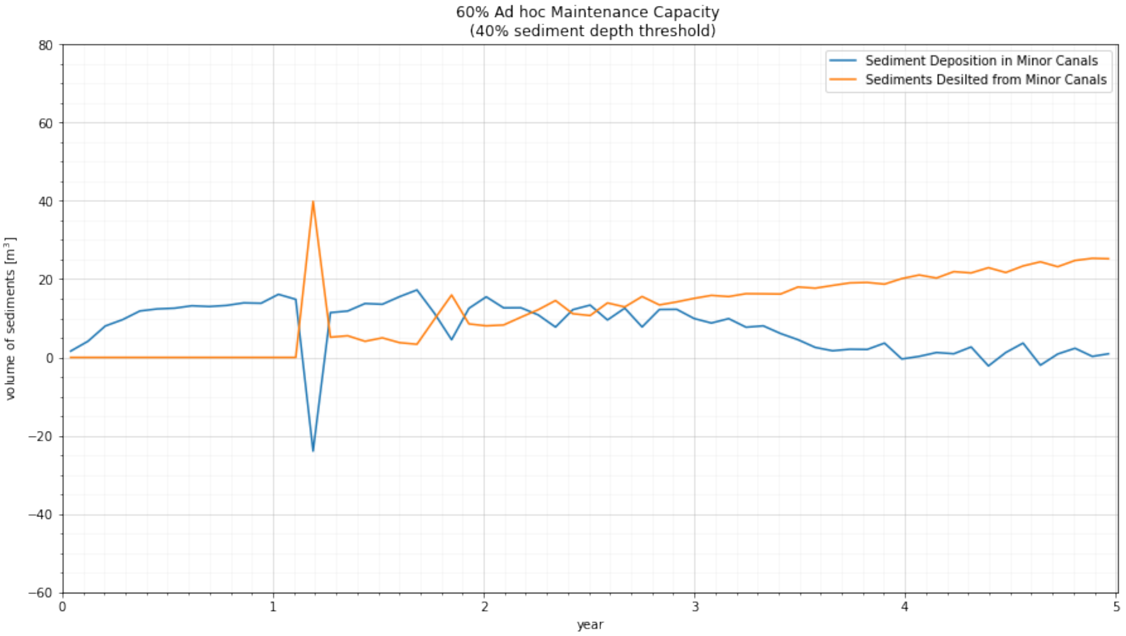


(a) 20% ad hoc maintenance capacity.

Figure A.17: Change in sediment deposition & removal at varying cap_a & $h_{s,\%}$=40%.

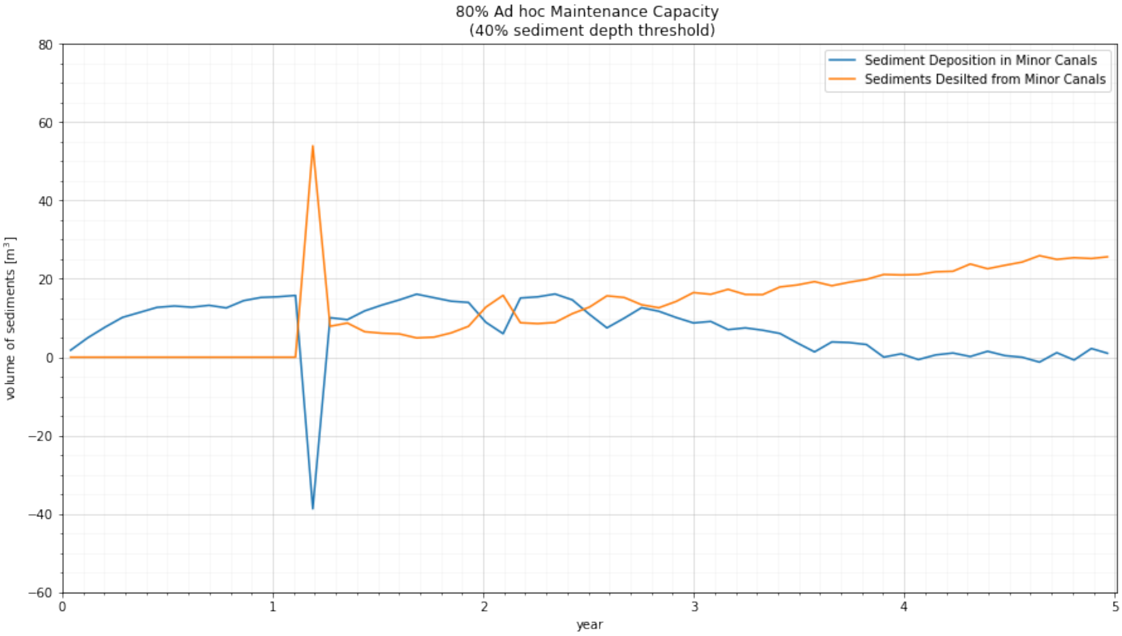


(b) 40% ad hoc maintenance capacity.

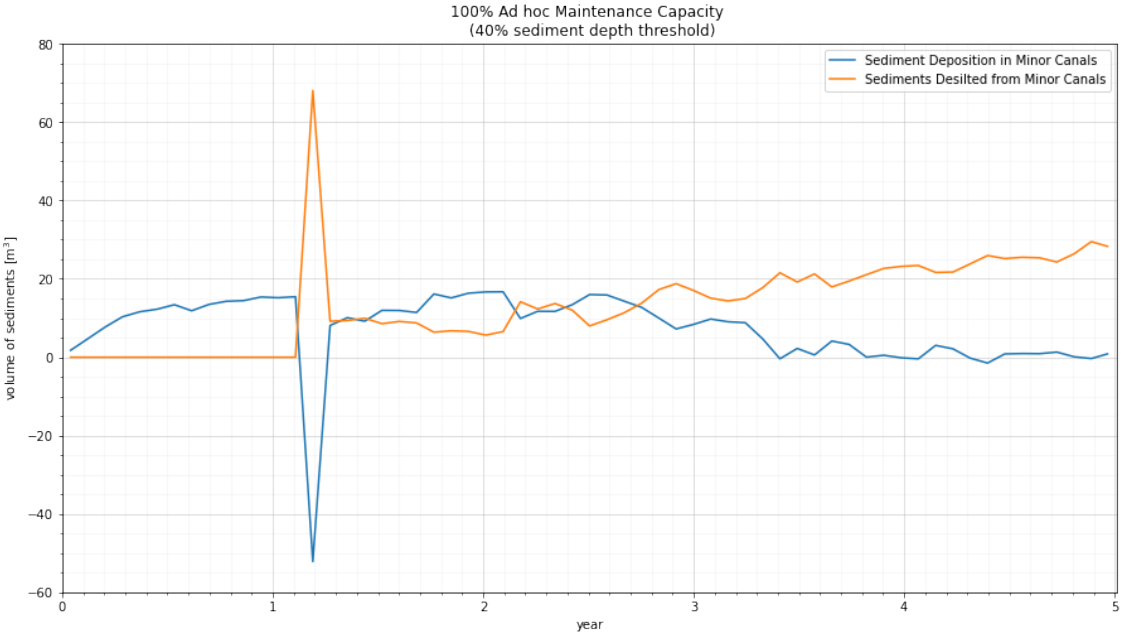


(c) 60% ad hoc maintenance capacity.

Figure A.17: Change in sediment deposition & removal at varying cap_a & $h_{s,\%}$=40% (continued).

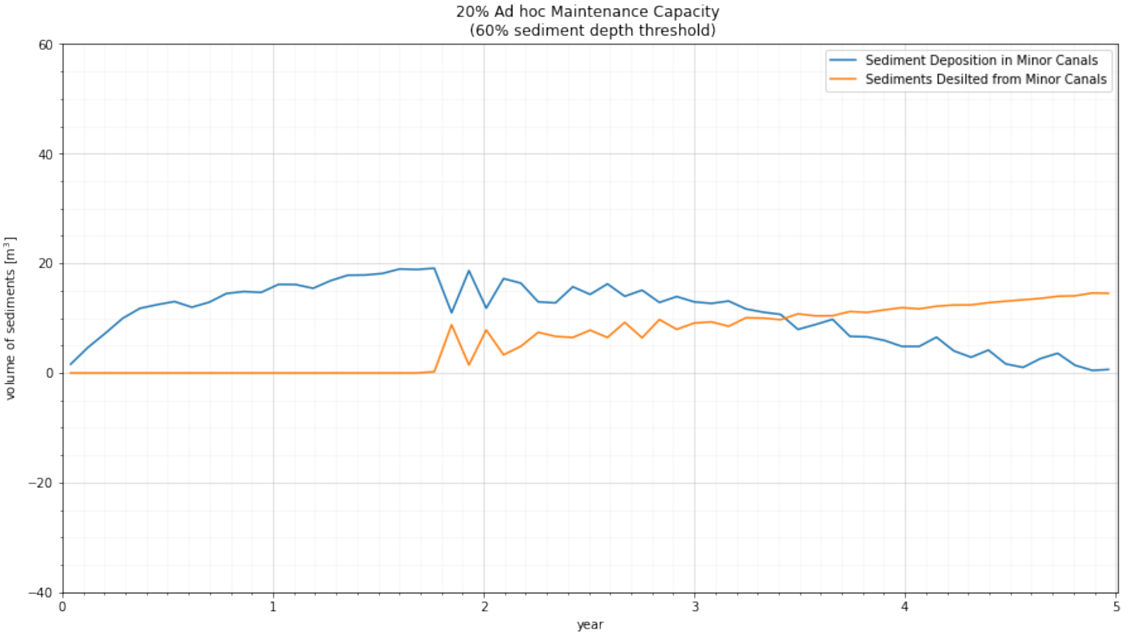


(d) 80% ad hoc maintenance capacity.

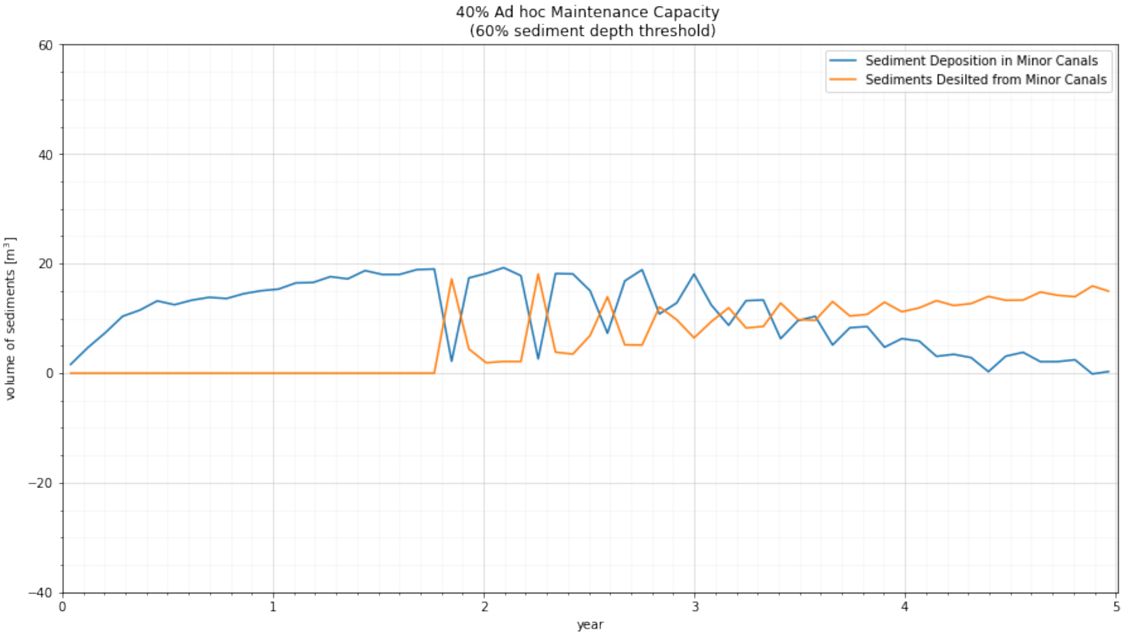


(e) 100% ad hoc maintenance capacity.

Figure A.17: Change in sediment deposition & removal at varying cap_a & $h_{s,\%}$=40% (continued).

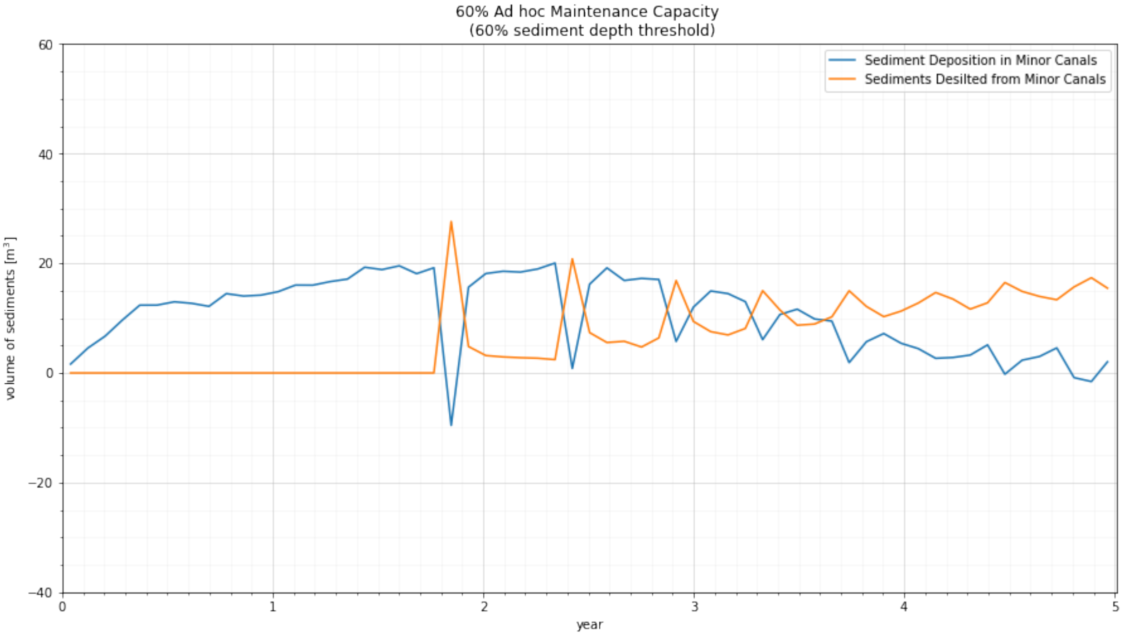


(a) 20% ad hoc maintenance capacity.

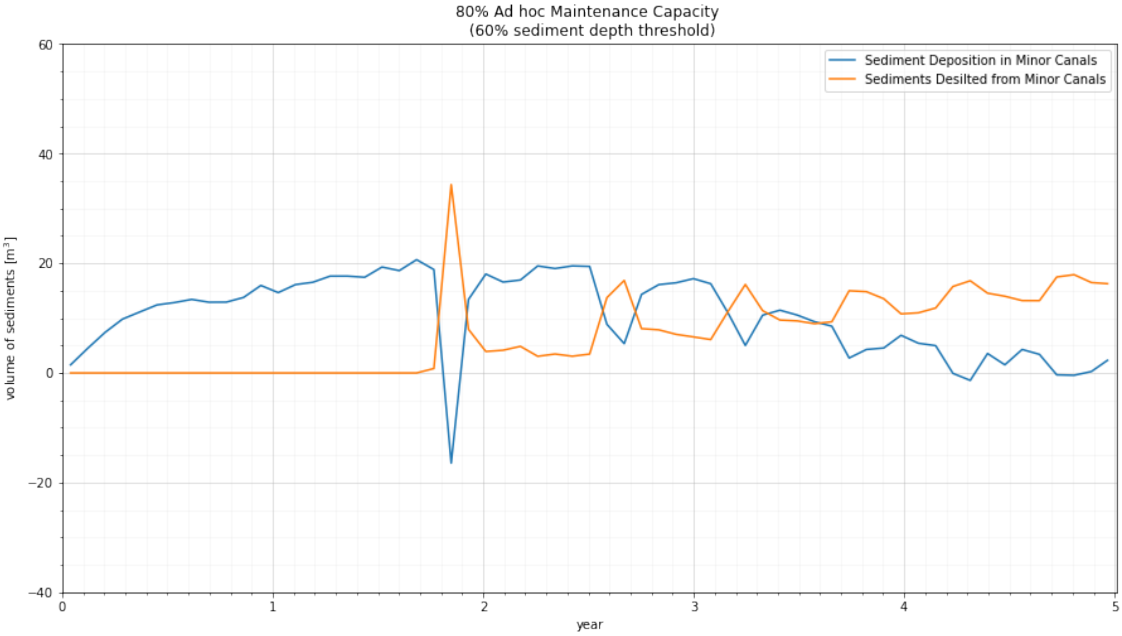


(b) 40% ad hoc maintenance capacity.

Figure A.18: Change in sediment deposition & removal at varying cap_a & $h_{s,\%}$=60%.

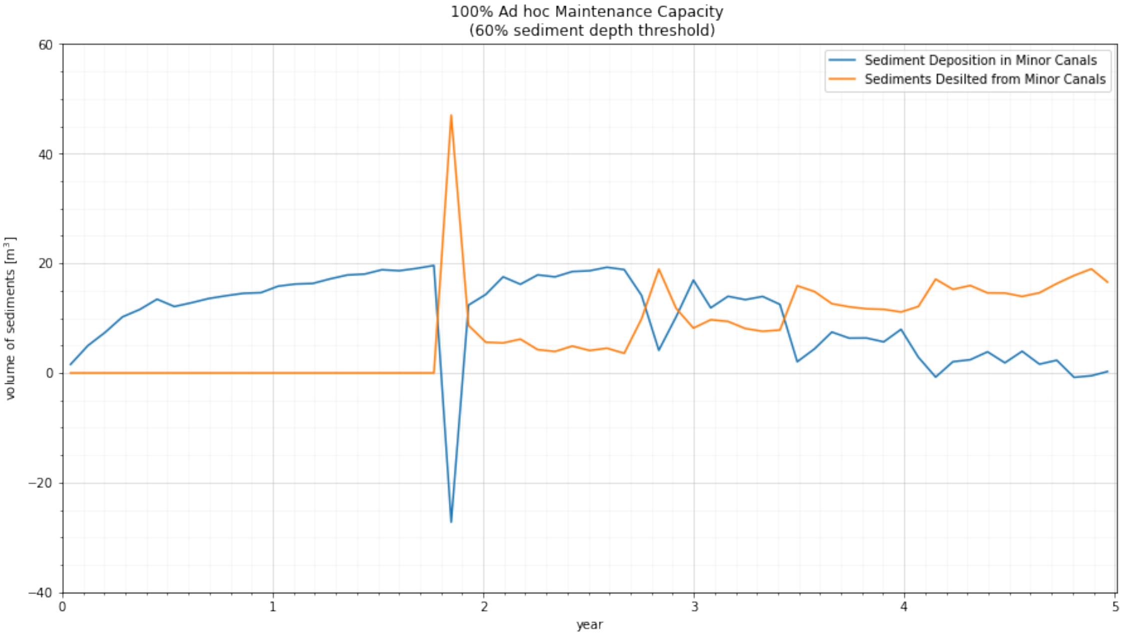


(c) 60% ad hoc maintenance capacity.



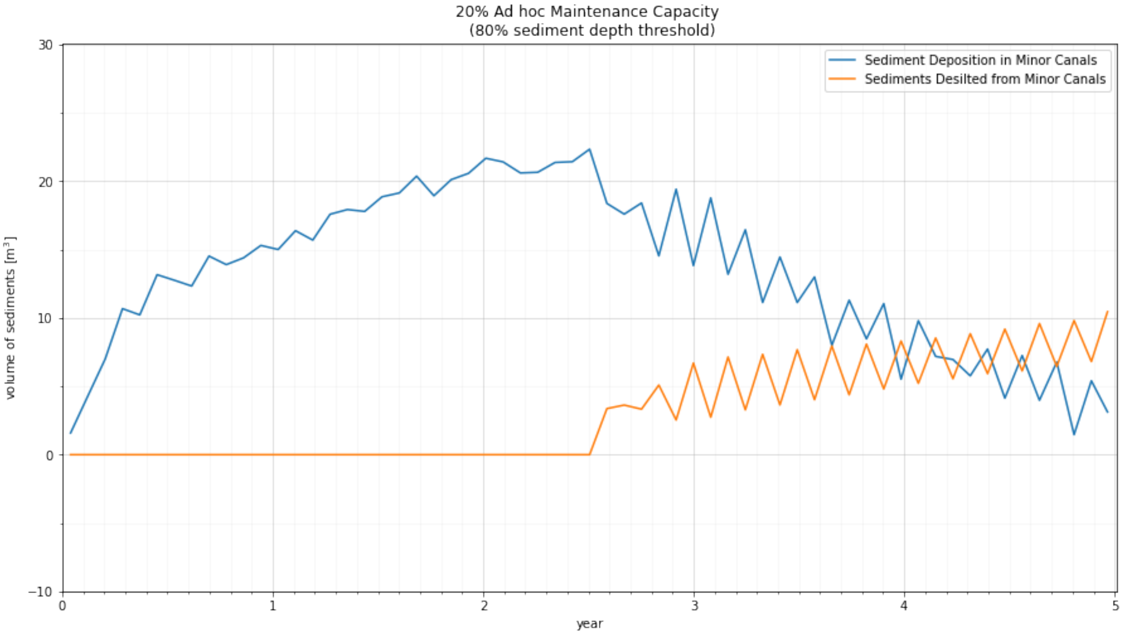
(d) 80% ad hoc maintenance capacity.

Figure A.18: Change in sediment deposition & removal at varying cap_a & $h_{s,\%}$=60% (continued).



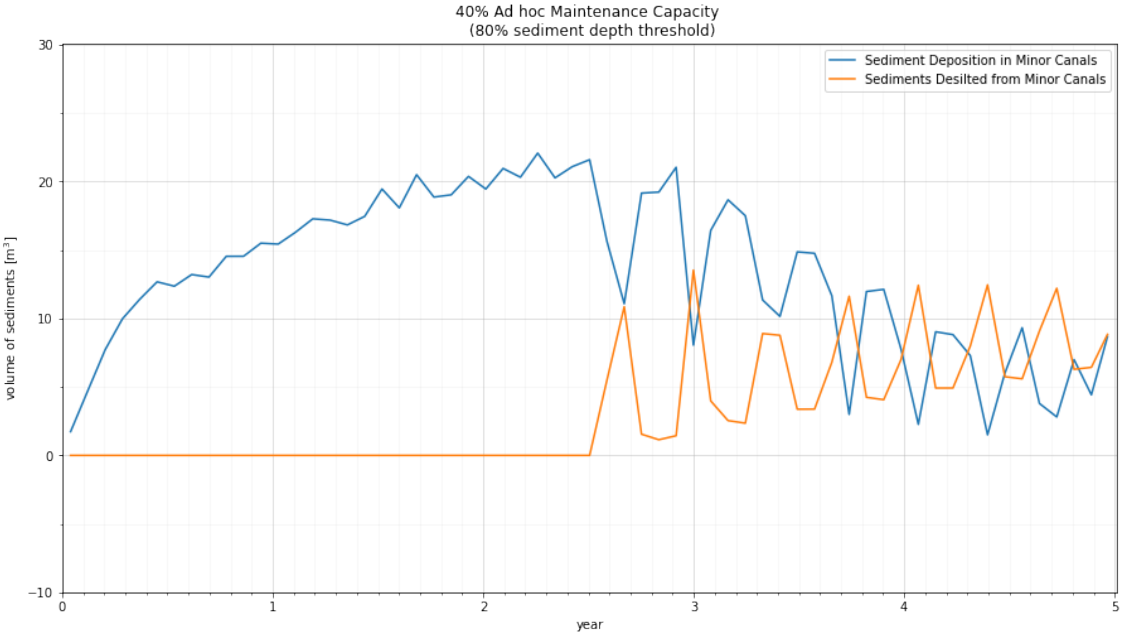
(e) 100% ad hoc maintenance capacity.

Figure A.18: Change in sediment deposition & removal at varying cap_a & $h_{s,\%}$=60% (continued).

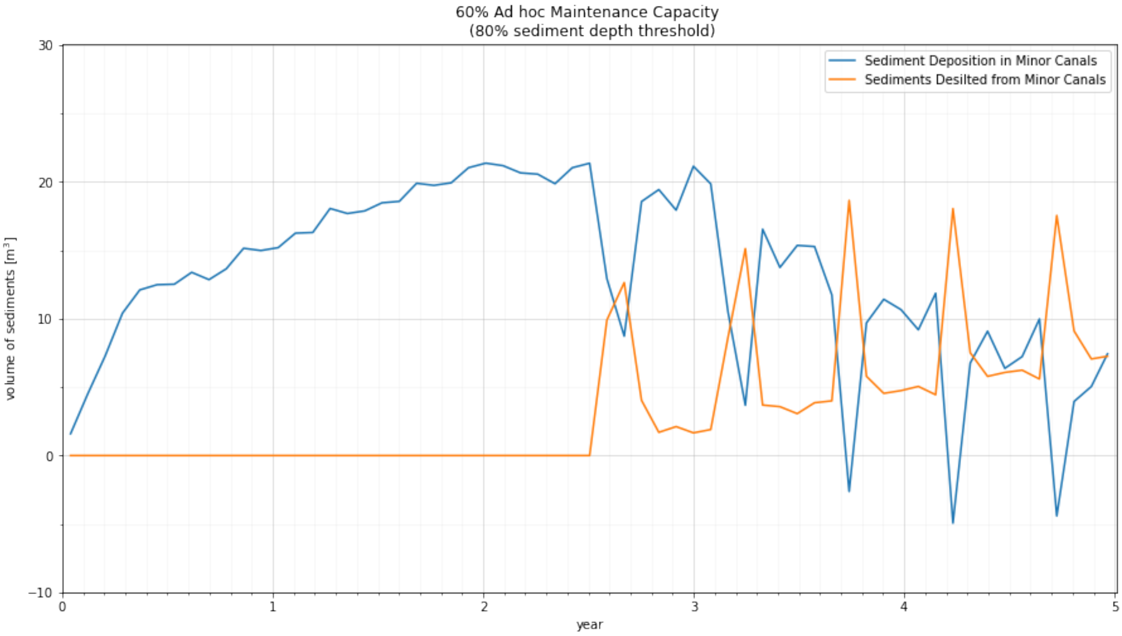


(a) 20% ad hoc maintenance capacity.

Figure A.19: Change in sediment deposition & removal at varying cap_a & $h_{s,\%}$=80%.

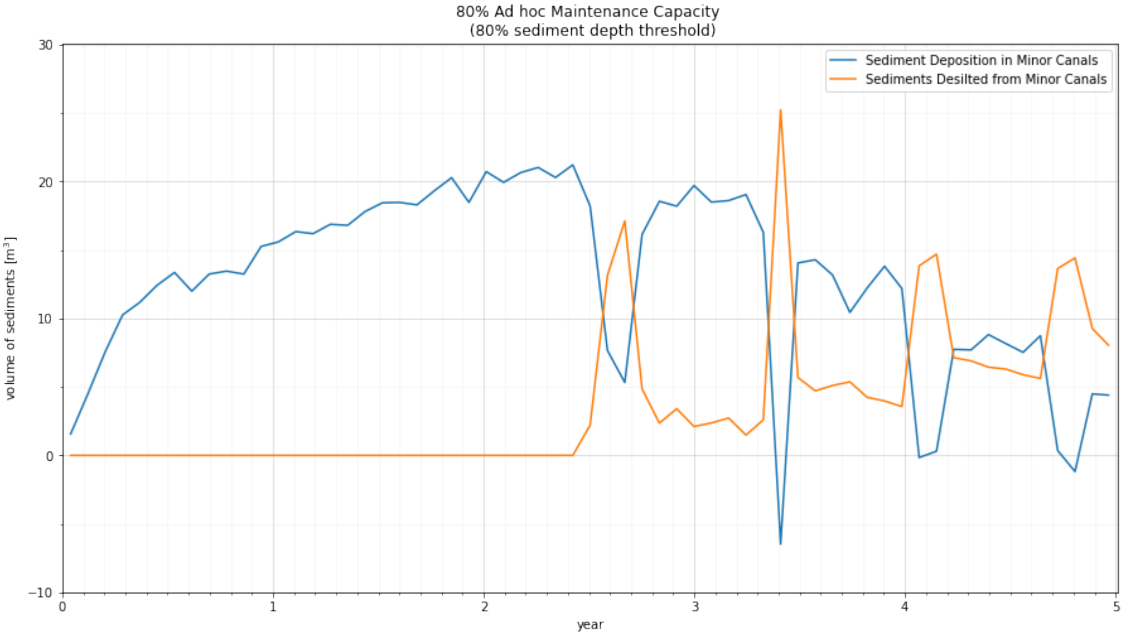


(b) 40% ad hoc maintenance capacity.

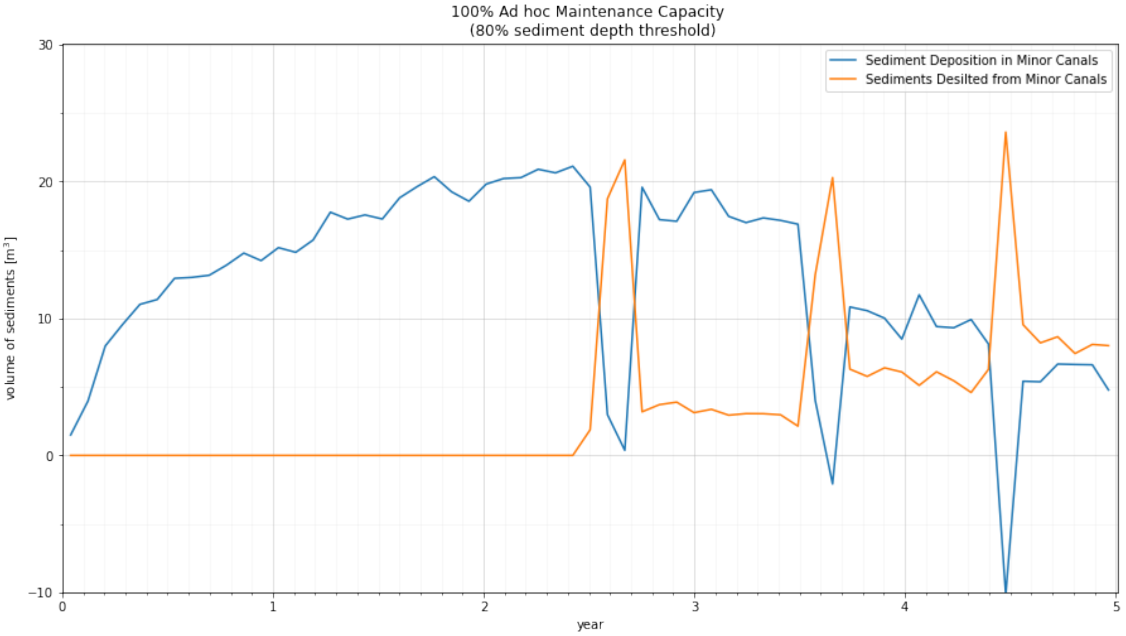


(c) 60% ad hoc maintenance capacity.

Figure A.19: Change in sediment deposition & removal at varying cap_a & $h_{s,\%}$=80% (continued).

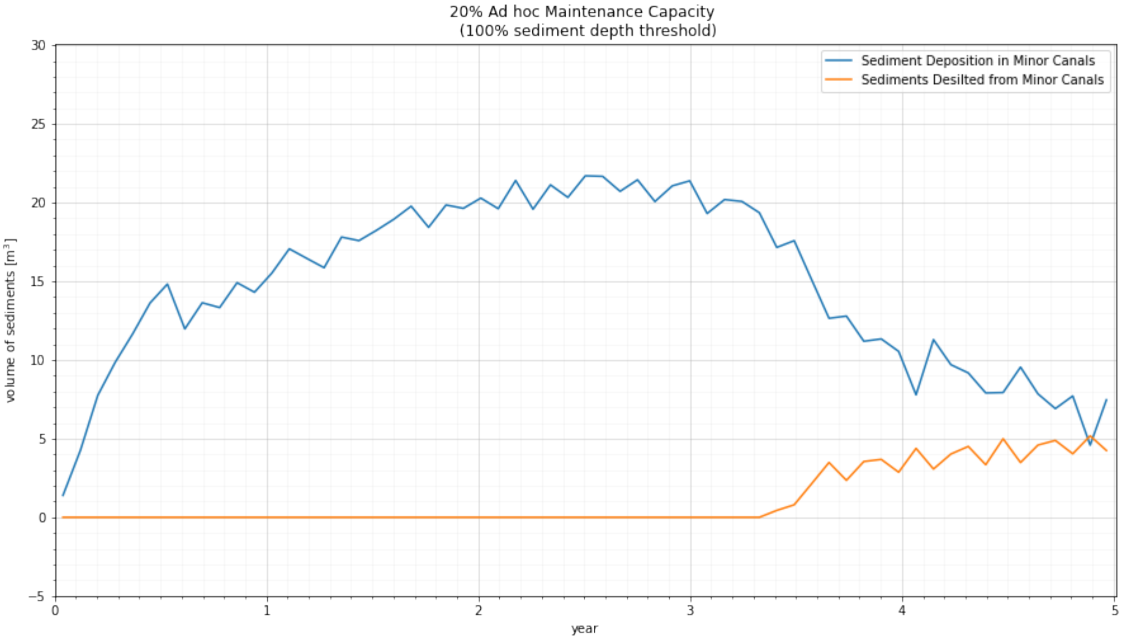


(d) 80% ad hoc maintenance capacity.

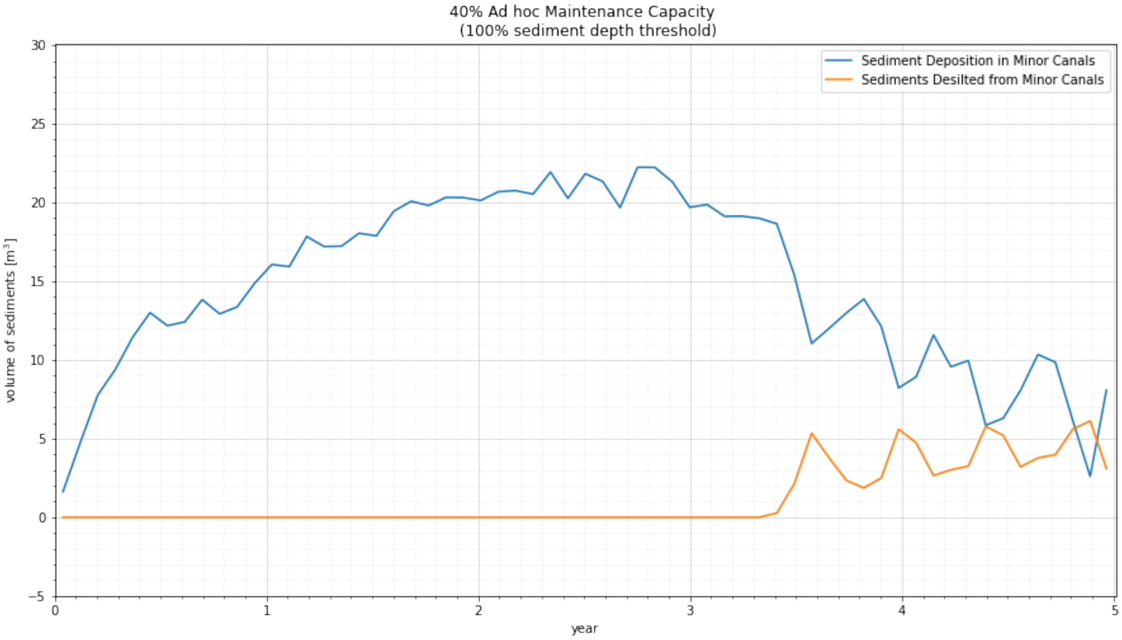


(e) 100% ad hoc maintenance capacity.

Figure A.19: Change in sediment deposition & removal at varying cap_a & $h_{s,\%}$=80% (continued).

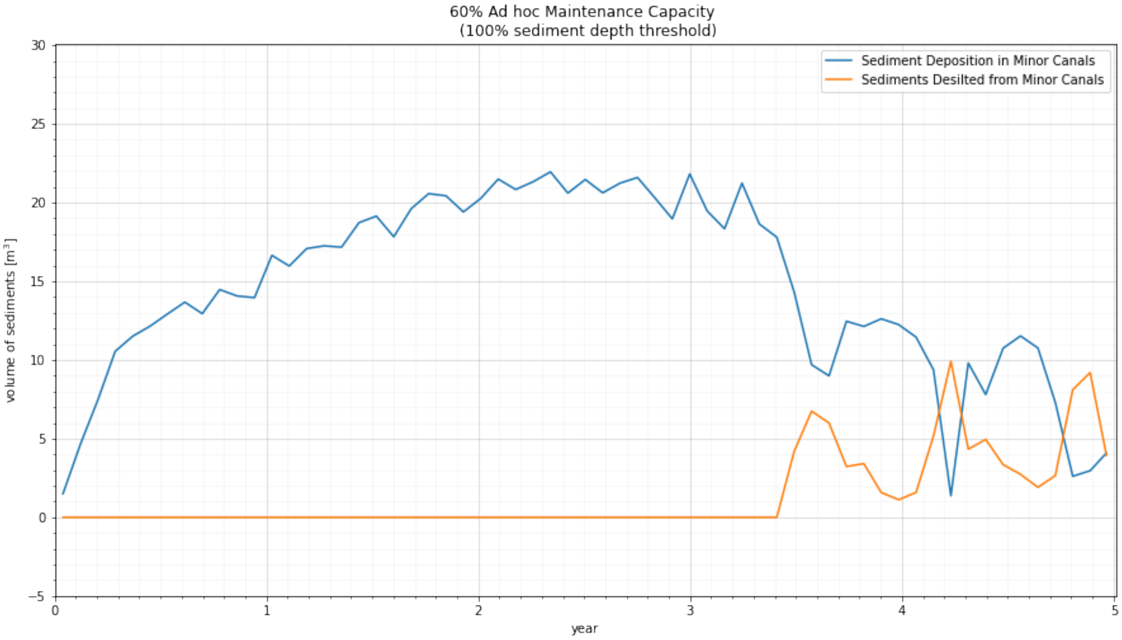


(a) 20% ad hoc maintenance capacity.

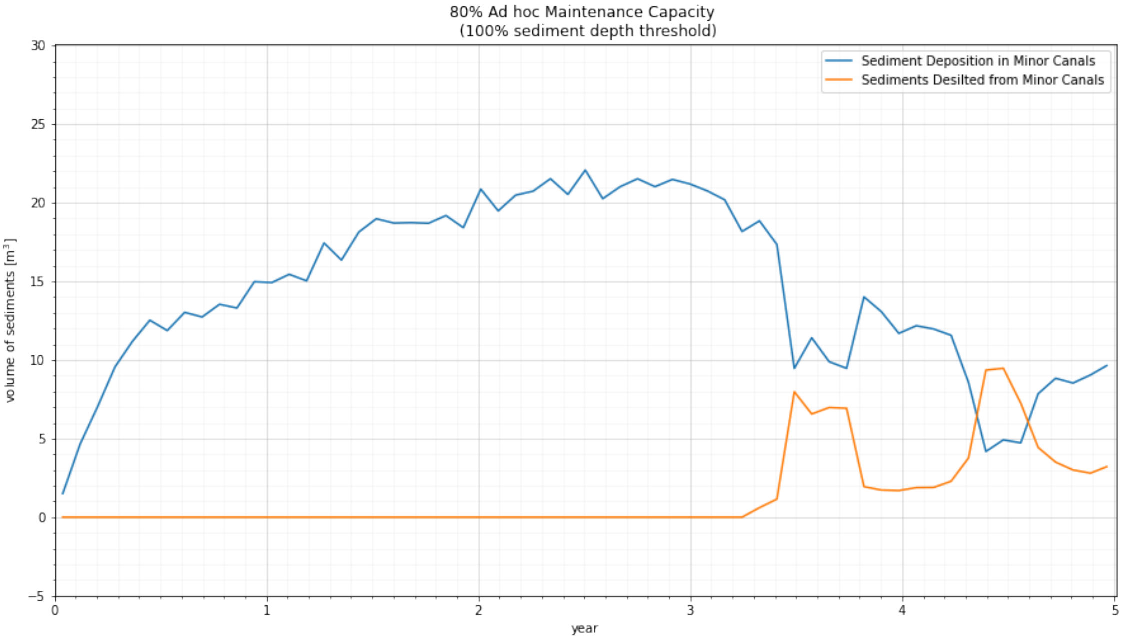


(b) 40% ad hoc maintenance capacity.

Figure A.20: Change in sediment deposition & removal at varying cap_a & $h_{s,\%}$=100%.

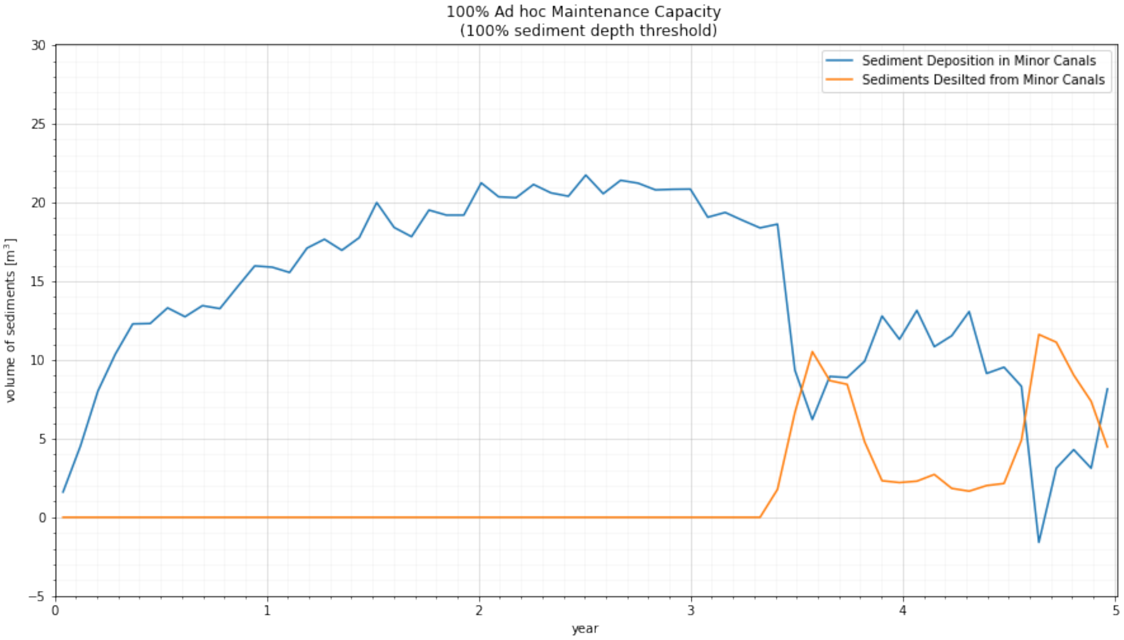


(c) 60% ad hoc maintenance capacity.



(d) 80% ad hoc maintenance capacity.

Figure A.20: Change in sediment deposition & removal at varying cap_a & $h_{s,\%}$=100% (continued).



(e) 100% ad hoc maintenance capacity.

Figure A.20: Change in sediment deposition & removal at varying cap_a & $h_{s,\%}$=100% (continued).