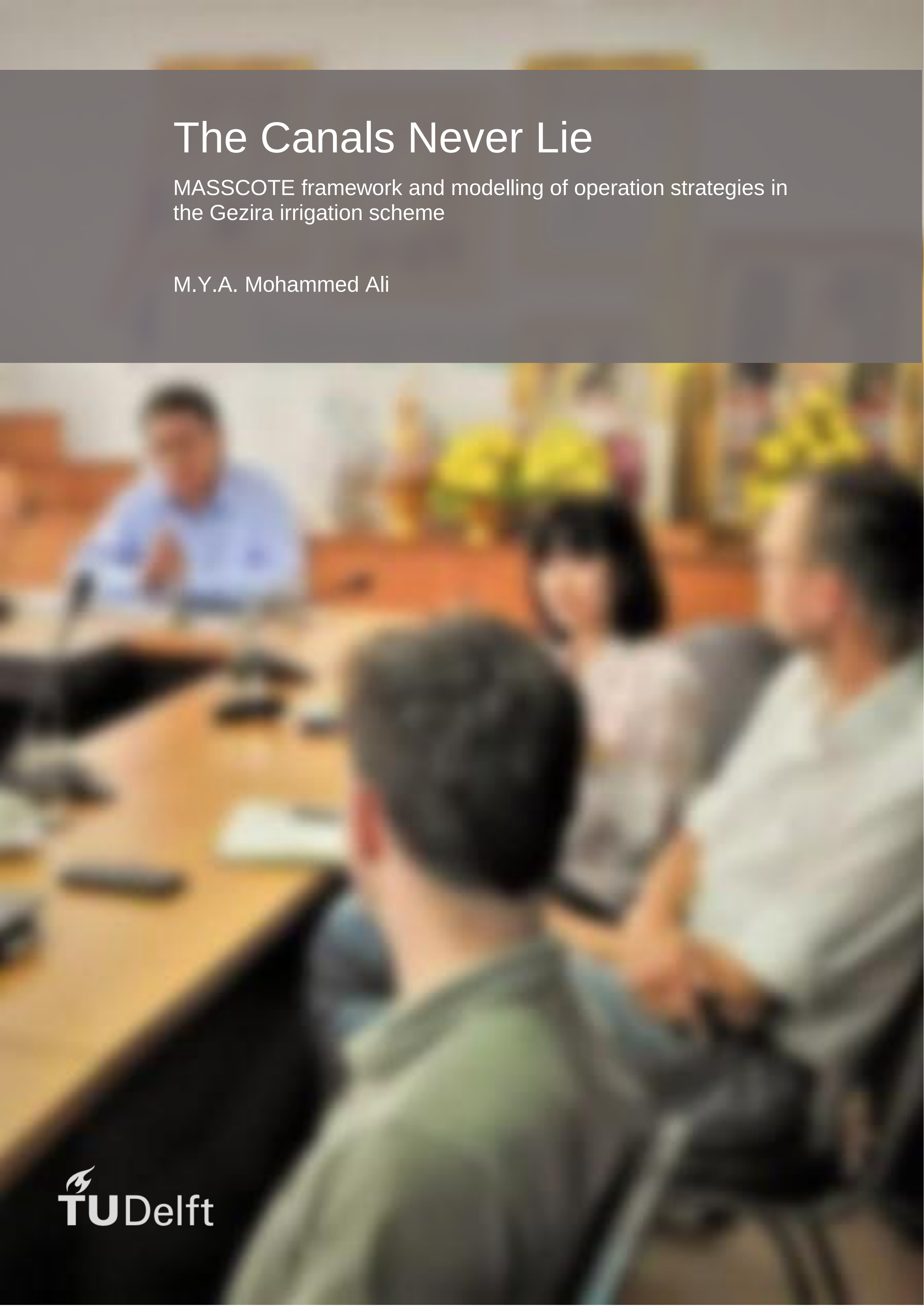
The Canals Never Lie

MASSCOTE framework and modelling of operation strategies in the Gezira irrigation scheme

M.Y.A. Mohammed Ali



The Canals Never Lie

MASSCOTE framework and modelling of operation strategies in the Gezira Irrigation Scheme

By

M.Y.A. Mohammed Ali

In partial fulfilment of the requirement for the degree of

Master of Science

In Water Management

At the faculty of Civil Engineering and Geosciences at Delft University of Technology,

To be defended publicly on 27th of November, 2020 at 09:00 AM.

Supervisor:	Dr.ir. Maurits W. Ertsen (Chair)	TU Delft
Thesis committee:	Dr. Ronald van Nooyen	TU Delft
	Dr. ir. Leon Hermans	TU Delft

Summary

The Gezira irrigation scheme, in Sudan, stretches out south of Khartoum between the Blue Nile and the While Nile Rivers. For more than 95 years since its establishment in 1925, the scheme has been a significant asset to Sudan's economy. It is considered one of the oldest and largest schemes in the world being served by one management body using surface gravity irrigation from a single source. For many years, the system has performed with high efficiency and was considered a good model example, both locally and internationally.

In the last few decades the scheme has deteriorated. The water productivity records show declining trends, while more water is being withdrawn from Sennar dam. Farmers are complaining about water shortages and some fields are not reached at all. Authorities state severe damages in the system's infrastructure, with about 85% of the system's hydraulic works being damaged. The performance of operation is well below the required efficiency. The sedimentation issue has always been present in the system, especially in the minor canals, but has been severe in recent years. As a result, farmers tend to interfere in the operation of the system, as they are not satisfied with the management authorities. Therefore, the scheme's operation situations changed accordingly, shifting from the original design approach into new – often undesired – situations.

There have been many studies carried in the Gezira Irrigation scheme, in order to understand the reasons behind this deterioration and find sustainable solutions. Starting from the causes of the sedimentation issue and maintenance works, generating new methods of calculating the crop water requirements using remote sensing, influence of farmers' practices on field level, change of management and institutions throughout the history, and many others. Yet, there is no sensible change seen on the ground.

The main objective of this thesis is contribute to the researches done in the Gezira scheme by providing an understanding of how the canalization system's respond to various water demands strategies. In recent years, there has been a noticeable improvement in methods used to determine crop water requirements using remote sensing. Coping with these improvements, a main question rises, to what extent these remote sensing approaches could be implemented in large irrigation schemes, taking the Gezira scheme as a case study. Determining water requirements is one thing, delivering the water through the canal system could be something else.

In order to answer the above question, we first need to analyze the system we are studying. This step was carried through analyzing the current, general, performance of the Gezira scheme and comparing it to the initial design characteristics of the scheme using the MASSCOTE framework (FAO). Using the outcomes of the MASSCOTE evaluation, the thesis proceeded by generating a computer model of the canalization system, taking a major and minor canal as a representation for the water distribution system, and testing different water demands scenarios. This step provided insights into the operation of the canalization system on the level of major and minor canals. It was found that, within the boundaries of our model, implementing new remote sensing methods is practicable, assuming water is readily available at the offtake of the major canal. This conclusion takes into consideration the lengths of the canals and their locations regarding the overall scheme and the carrying capacity of each canals.

Acknowledgments

First and foremost, I would like to express my deep and sincere gratitude to my supervisor, ir.Dr. Maurits W. Ertsen for guiding me through this study. From the beginning in formulating the thesis objectives and methodology and for always taking the initiative to assist me until defending my thesis. I look forward to working with him in the future. Also, my appreciation to Dr. Ronald van Nooyen and Dr. ir. Leon Hermans for being part of the thesis committee.

To the Delft Global Initiative, especially Sophie Oostelbos, without their financial and social support this study would not have seen the light.

To my mother Amany, words cannot express my gratitude nor thankfulness for everything you have provided and keep providing me with. I will always be in debt to you with my life.

To my father Yasir, my genuine role model in this life, who taught me everything and enlightened my road. You were always with me in this journey. I truly hope one day to become like you.

To my sisters Amoona and Leena and best, right arm, brother Osama. My apologies for not being there when you needed me.

To my amazing second family in the Netherlands Ali, Mohamed, Amna, Rayan who contained and lifted me when needed. To my brothers Mohammed Talaat and Moatasim Ismaeil.

To my dearest brothers and friends in Sudan, thanking you is never enough.

Lastly and most preciously my wife, Sawsan, you have always been my motivation, encouragement, and strength.

I would like to dedicate this work to the Sudanese glorious December revolution, and to all the martyrs who redeemed their souls for a better Sudan. This work is intended towards walking a step ahead on the mile road for a developed Sudan.

Contents

List of Tables

List of Figures

1. Introduction

1.1. General

In recent years, improving the water management in irrigation schemes has become a necessity. The increasing demand for agricultural food production aligned with scarcity in water resources posed new challenges for the management of the existing irrigation schemes. As declared by the FAO in 2009, 90% of global growth in crop production (80% in developing countries) is expected to come from higher yields and increased cropping intensity, with the remainder coming from land expansion. In fact, extensive investment in irrigation infrastructure, as seen around the world in the second half of the 20th century, has proved to be insufficient (Goelnitz & Al-Saidi, 2020). Confirming these claims, Tygai (2017) states that agricultural production must increase by 100% in developing countries to feed the growing population. To be able to meet this growing food demand and achieve higher yields, many factors are involved in contributing to this process, for example the economic, social, and political factors. They all have their contributions and influences. In addition, one of the main significant factors is irrigation water management.

Irrigation water management is an old mechanism, dating back thousands of years. As defined by Kelly (2012), “it is the act of timing and regulating irrigation water application in a way that will satisfy the water requirement of the crop without wasting water, energy, and plant nutrients or degrading the soil resource”. Throughout our history of mankind, there has been evidence of complex systems of water delivery for irrigation in numerous civilizations like Egypt, Mesopotamia and the Maya civilization in Central America. With time passing, more efficient irrigation systems have been developed. Nowadays, engineers search for the optimum operation of a system with minimum use of resources (human and non-human). The development of irrigation schemes has greatly expanded after the Second World War, as governmental and international (donor) investments peaked in the 1970s. According to Seibert et al. (2013), on a global level, more than 300 million hectares are today equipped for irrigation (69% in Asia, 17% in America, 8% in Europe, 4% in Africa, 2% in Oceania), with the majority (62%) irrigated with surface water. By consuming a 70% share of all freshwater withdrawn globally and up to 95 % in developing countries, agriculture is the largest water use sector (Seibert et al., 2013).

Many surface irrigation schemes in developing countries in general and in Sudan in particular perform well below their design potential in terms of crop productivity, water dependability, equity, and efficiency (Mohamed et al, 2010). This is linked to many reasons, such as systems deterioration, change in management and operation strategies, social impacts, change in project goals, and many others (. In order to find sustainable solutions, hence improve the performance of these irrigation projects, critical analysis is carried to the structural (canals, hydraulics structures) and non-structural (management, operation and maintenance) of the system.

There are several approaches and frameworks used to evaluate the performance of irrigation scheme. One of the most widely used approaches is the MASSCOTE framework developed by FAO. It has been applied in various irrigation schemes worldwide (Asia, Africa, South America) and proven its efficiency (FAO). The MASSCOTE framework investigates the performance of the system through analyzing its canalization system. It follows the principle that critical examination of the canal system and the way it is operated, reflects key evidence about the operation management and the service to farmers. In addition to the analysis, it works towards providing a better modernization plan for enhancing the water use service delivered to farmers as end users.

Our case study concerns the Gezira Irrigation Scheme. The scheme has received a lot of attention from researchers and international organizations throughout its history. There are several studies on the rehabilitation of the scheme and possible reasons for its poor performance (Goelnitz & Al-Saidi, 2020). Despite this massive attention, the scheme is continuing to decline every year to a worse status. Many efforts were focused on rehabilitating infrastructure and removing of sediments, but it always turns out to be costly and does not solve the issue at the end (Al Zayed et al., 2015).

1.2. Scope of the study

The Gezira scheme is a large scheme with many aspects to consider. As mentioned before, there has been many studies done in the Gezira scheme for development and modernization, taking various components into consideration. In this study, we will tackle the aspect of determining the water demands and how this can improve the water use, if water is delivered as required. This includes investigating the different methods of determining the crop water requirement and how the system responds to these water demands under the given operation strategies.

Taking the first step, an entering door to the Gezira scheme's characteristics and issues was needed. From literature and official reports about the Gezira, an integrated, rigid, framework used for performance assessment, was not found. Therefore, the idea of using MASSCOTE framework as guiding approach for the general assessment of the scheme's performance was proposed. The MASSCOTE provides a broad general idea of the system's characteristics. In such a large scheme with many issues, we had to focus on a particular issue and try to understand it better, in order to find feasible solutions for it. It was found that, together with the part of determining crop water requirements which had low attention in the Gezira scheme, there has not been any study in investigation how the Gezira canal system responds to the different water demands methods.

Determination of crop water requirement marks the first step in the process of irrigation and operation management. Then, the crop water requirements are turned into water demands, that are required to be met by the water delivery system. Therefore, this thesis will analyze the performance of the system in terms of its ability to meet the crop water requirements. The Gezira irrigation scheme had a typical, old, water demand method since it's established in 1925, called the duty method: a method depending only on the cultivated crops area multiplied by one constant factor. In the 1970s, a new crop water requirement method was introduced by Farbrother, where the crop water requirement depends on crop stages and weather conditions. In recent years, new remote sensing methods appeared, in which satellite data are used in determining the cropped areas and their actual evapotranspiration of the crops (Ahmed et al., 2010). The first two methods have been implemented in the Gezira scheme during different eras. They were always calculated and organized beforehand, hence irrigation operation was scheduled beforehand as well. In this thesis, we want to investigate how the canalization system responds, both spatially and temporally, under these different crop water requirement methods, and whether the canalization system can cope with the remote sensing methods (real time) in terms of water delivery.

1.3. Readers guide

Chapter 1 reflects the growing agricultural food demand and the urge need for efficient water management in large surface irrigation scheme. It then dives into our case study of the Gezira scheme illustrating the ideas driving the thesis.

Chapter 2 gives a brief history about irrigation in Sudan and the development of large irrigation schemes. Then it provides more insights into the general characteristics of the Gezira scheme such as soil, cropping pattern, and climate.

Chapter 3 represents the application of the MASSCOTE approach in the Gezira scheme, where two Gezira happened to be found: Gezira from official documents and Gezira from ground data. This chapter serves as an entry point to the modelling chapter four.

Chapter 4 presents the model development using the SOBEK program. It illustrates all the input data used in the model, the model setup, and the generation of scenarios. Three phases were modelled: the Major canal, a minor canal, and a combined system of both. It also reflects the results of the different phases of the modelling.

Chapter 5 contains the final discussion and conclusion of the report.

2. Brief History of Gezira

2.1. Irrigation in Sudan

Sudan is endowed with large agricultural areas. The arable agricultural area is about 84 million ha, where the irrigated area is estimated to be more than 2 million ha (Osman et al, 2011). With these numbers Sudan ranks as the largest irrigated area in sub-Saharan region and the second largest in all Africa after Egypt (Nile Basin Initiative, 2009). The Nile and its tributaries are the main sources of irrigation water for the Sudanese irrigation schemes. The governmental schemes account for about 93% of the irrigated area, where the rest belongs to the private sector. The main type of irrigation in these schemes is surface, gravity, irrigation. Surface irrigation is considered to be one of the least costing irrigation types (Tyagi, 2017). Although, Sudan has all this potential agricultural land and water, thus they have been used to a very limited extent, and that is mainly due of poor water resources management practices (Mahjoub, 2014).

Establishment of large irrigation schemes in Sudan began in the 1920s. The Gezira scheme, the first large irrigation scheme, was built in 1925, after the completion of the Sennar dam (Plusquellec, 1990). Quite frankly, Sennar dam was built for the main purpose of providing irrigation water for the Gezira scheme, then later hydropower units were installed. The first phase of the Gezira establishment was an area of 350,000 ha, then extended gradually to more than 880,000 ha after the development of the Managil Extension in the 1962 (Elshaikh, 2020). The Gezira scheme was considered as a successful model and encouraged the Sudanese government to develop more similar irrigation schemes. In the early 1950s, the Sudanese government started constructing a number of large irrigation schemes, most of them on the Blue Nile River. These include the Junayd Scheme on the right bank of the Blue Nile River and east of the Gezira Scheme with a total area of 36,000 ha (Osman, 2015). Similarly to the Gezira, cotton was the main crop grown until 1960, when about 8,400 ha were converted to sugarcane. In the early 1970s Al Suki Scheme was established upstream of Sennar Dam to grow cotton, sorghum and oilseeds with a total area of 36,000 ha. The Rahad irrigation scheme was built in 1979, with an area of 63,000 ha (Hamid et al, 2011). The irrigation water comes from a seasonal tributary of the Blue Nile called Rahad river. A small barrage is built in the river to divert water to the scheme. Several small Blue Nile pump irrigated schemes were established as well. They added more than 80,000 ha to Sudan's overall irrigated area (MoIWR, 2020). Figure 1 illustrates the irrigation schemes along the Blue Nile river.

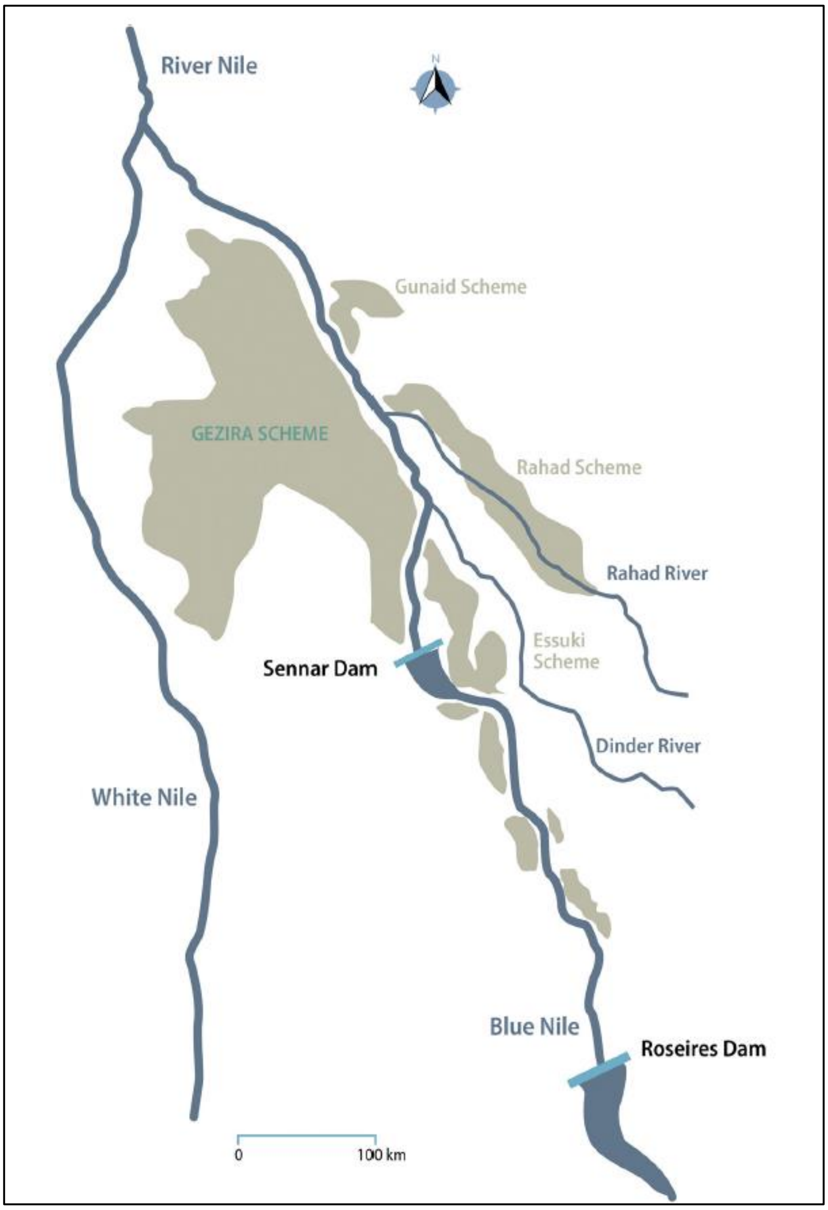


Figure 1. Mega Irrigation schemes in Sudan (Goelnitz & Al-Saidi, 2020)

2.2. Background information on Gezira Scheme

The Gezira Scheme is one of the oldest and largest irrigation schemes in the world being operated under one single management. It is located between the Blue Nile and the White Nile Rivers. It is geographical location lies south of Khartoum (capital city of Sudan) and North of Wad Madani city, as shown in figure 2 below. The scheme consumes up to 43% of the Sudan's current allocation of Nile water, about 8 billion m^3 per year (HRC, 2018). Two main canals, Gezira and Managil canals, supply the water requirement to the scheme from Sennar Dam with a combined design capacity of 354 m^3/s. The initial objective of the scheme was to provide cotton for Britain's textile industry during the colonization period. Later after the independence in 1956, it became a national asset belonging to the Sudanese government. The scheme reached today's size with the Managil Extension through the construction of the Roseiries Dam in the early 1960s. Gezira Scheme produces 60% of the country's cotton, 75% of wheat, 35% of sorghum, 15% of groundnut and 20% of vegetables (Osman, 2016; Goelnitz & Al-Saidi, 2020). In addition, it contains more than 1.7 million of livestock (cattle, camels, sheep and goats). This makes it one of the most important schemes for food security in the country. Its contribution to the national economy of the country is significant. The total number of farmers in the scheme is about 114,000 among them 12,000 females (Mohamed, 2010). Beyond the canalization network, the scheme's infrastructure includes machinery, equipment, staff housing, roads and vehicles. The value of the infrastructure is roughly estimated to amount to 8 billion USD (Wallach, 1988) . In recent years the productivity of the scheme has declined. The land productivity was mostly between 1 to 3.2 tons/ha for sorghum, 0.6 to 2.4 tons/ha for wheat and 1.1 to 2.5 tons/ha for groundnuts compared to the optimum yield obtained at Gezira Research Station is 4.75 tons/ha, 3.57 tons/ha and 5.5 tons/ha for sorghum, wheat, and groundnut, respectively (Adeeb, 2006).

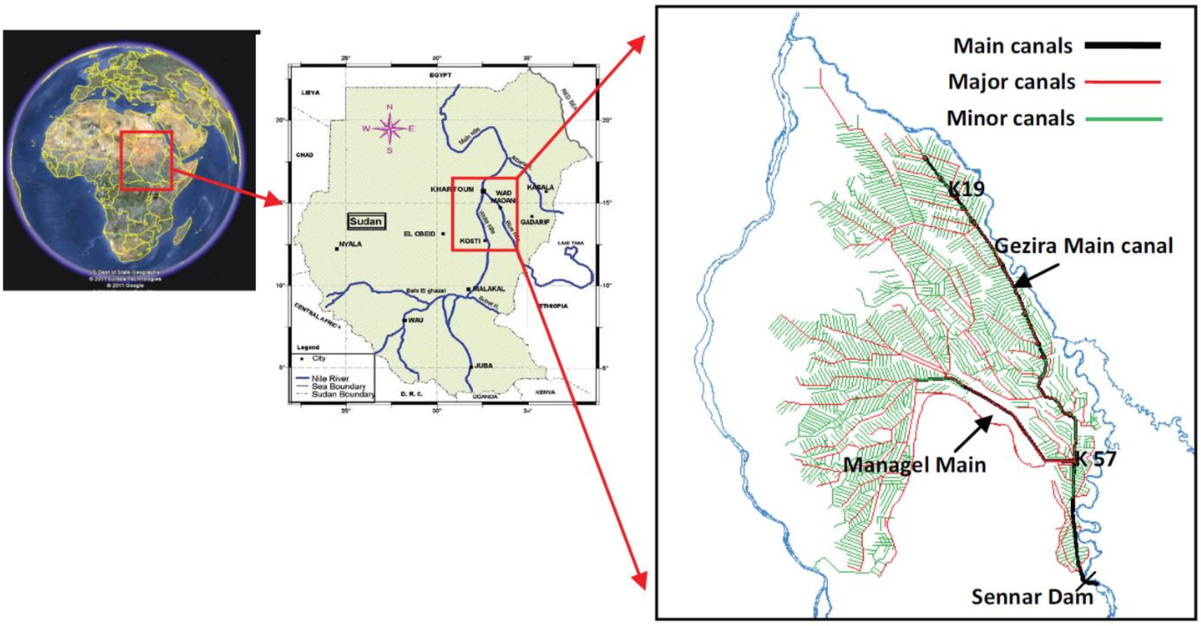


Figure 2. Gezira scheme location and layout (Elshaikh, 2020)

2.3. Climate

The Gezira Scheme is located in a semi-arid region, characterized by low average annual precipitation and relatively high evaporation rates. The average annual rainfall ranges from 470 mm in Sennar to 160 mm in Khartoum, from June to September. The average annual rainfall is estimated about 300 mm in Wad Madani (Ahmed et al., 2010). The relative humidity fluctuates from 20% to 70% and temperature varies from 5 ^{o}C in December to over 46 ^{o}C in April, with an annual mean of 28 ^{o}C. The reference evapotranspiration, ETo (Penman), at Wad Madani varies from 5.5 mm/day in December to 9 mm/day in June, with an annual average of 2,630 mm (Plusquellec, 1990). Table 1 below summarizes the meteorological data for Wad Madani station, which is the nearest station to the scheme.

Table 1. Meteorological data for Wad Madani station in 2012, (Meteorological Corporation Records)

Month	**Mean temperature (˚C)**		**Relative humidity (%)**	**Rainfall (mm)**	**Sunshine (hr)**	**Wind speed (knots)**
	Max	**Min**				
January	33.9	15.3	19	0	10.5	5
February	38.4	19.1	23	0	10.1	6
March	39.1	19.8	21	0	9.9	6
April	42.2	21.5	25	0	10.5	5
May	42.7	25.4	28	11.3	7.7	6
June	40	25.4	40	12.4	6.3	8
July	35.8	23.1	56	89.1	5.7	8
August	34	22.2	61	131	5.3	7
September	37.5	22.9	49	3.7	3.9	5
October	38.8	22.1	44	39.6	9.9	4
November	37.1	18.7	38	0.1	10.3	4
December	34.8	15.5	28	0	10.7	4

2.4. Soil and topography

The soil of Gezira Scheme can be classified as fertile flat central clay plains with a gentle slope to the Northwest. It is described by dark and heavy soils. The soil has a smectite clay fraction and is fine-textured, with 60 to 80% clay content. Smectite is the main mineral responsible for swelling and shrinkage during wetting and drying of soil. The very low water loss from this soil is due to negligible deep percolation in the field and low seepage from the canals (Plusquellec, 1990). Benefiting from these properties, we do not find canal lining in the canals of the Gezira scheme, neither consideration for deep percolation when calculating water demands.

2.5. Cropping Pattern

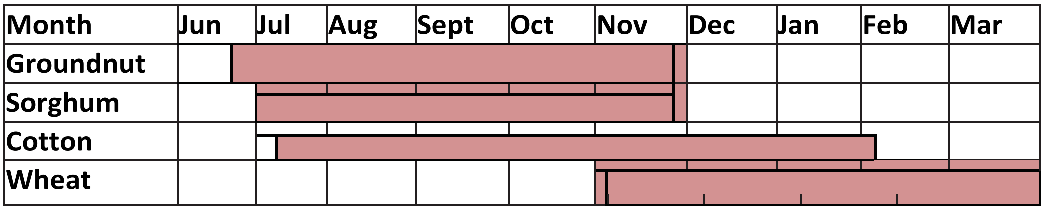
From the above introduction, building a dam mainly to provide irrigation water for such a large irrigation scheme, the reader might immediately conclude that irrigation water is main source of water. Yet, we find that irrigation in the Gezira is linked closely with the agricultural season, which is divided into to two seasons. The summer season (May – September) and winter season (October – March). In the summer season, irrigation is considered to be supplementary to the water coming from. While in winter season it is considered as the only main source for water. The period between March and May is specified for maintenance of the canals and the hydraulic structures (Elshaikh, 2018).

As stated earlier, the Gezira Scheme was established with the primary objective of producing cotton for the British Textile Factories. Thereafter sorghum, groundnut and wheat were introduced into the scheme later on. Over the last 70 years, several changes in the cropping pattern and course rotations have been implemented as shown in Table 2. In Table 3 a summary of the cropping calendar for the main crops in Gezira Scheme for the 2007/2008 season is shown.

Table 2. Cropping patterns over the years in Gezira Scheme (Sudan Gezira Board)

Season	Details of the rotation	Cropping intensity
1925 - 1930	Cotton – Dura / Lubia - Fallow - Cotton - Dura / Lubia - Fallow	(6 - Course) 66.6%
1931 - 1932	Cotton - Fallow - Fallow – Cotton - Fallow - Fallow	(6 - Course) 33.3%
1933 - 1960	Cotton - Fallow - Dura – Lubia / Fallow - Fallow - Cotton - Fallow - fallow	(8 - Course) 50%
1961 - 1974	Cotton - wheat - Fallow - Cotton - Lubia - Groundnuts – Dura / Philipasara - Fallow	(8 - Course) 75%
1975 - 1991	Cotton - Groundnuts - Dura/Vegetable - Fallow	(4 - Course) 80% or 75% in Gezira 100% in Managil
1992 - 2005	Cotton - wheat Groundnuts / Dura / Vegetable - Fodder - Fallow	(5 - Course) 75%

Table 3. Cropping calendar of the main crops for 2007/2008 (Osman, 2015)



Month	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar
Groundnut	🟥	🟥	🟥	🟥	🟥	🟥				
Sorghum		🟥	🟥	🟥	🟥	🟥				
Cotton		🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	
Wheat						🟥	🟥	🟥	🟥	🟥

2.6. Sedimentation in Gezira Scheme

Sedimentation is considered to be the biggest threat to the Gezira irrigation scheme. The scheme cannot be mentioned without bringing attention to the sedimentation issue. It is not only limited to Gezira scheme, but has always been a problem in the Sudanese projects. For example, the Sennar and Reseires reservoirs have lost their storage capacities by 71% and 34% respectively (Seleshi et al., 2008). According to the Hydraulics Research Center, the distribution of sediments entering the canals system is 5% in main canals, 23% in major canals and branches, 33% in minor canals and the remaining 39% goes to the fields. The major and minor canals suffer the most from sedimentation where huge volume of the conveyance capacity is lost due to sedimentation.

The records of MoIWR describe that between 1933 and 1938 the mean sediment concentration entering the Gezira Main Canal in August was only 700 ppm, while the average sediment concentration in August of 1988 and 1989 increased to 3,800 ppm; an increase of more than five (Plusquellec, 1990). The increase in sediment concentration continued to about 7,900 ppm in July 2003 (MoIWR). This increment reflects the serious land degradation and soil erosion in the river basin of the Blue Nile River. Poor land use practices, improper management systems and lack of appropriate soil conservation measures have played a major role of land degradation in the upstream of the Blue Nile River Basin (Seleshi et al., 2008). Gismalla et al., (2009) stated that the average annual sediment that is entering the scheme is about 8.5 million tons. Also, Elhassan and Ahmed (2008) pointed out that the annual amount of sediment deposition in the irrigation canals is about 16 million m^3, while El Monshid et al. (1997) reported that annually 19 million tons of sediment accumulated in Gezira Scheme. There is a great variation in the estimates of the annual sediment deposition in Gezira Scheme, which also reflects the uncertainty with these estimates. The sediments that accumulate in the head reach and along the canals create water delivery difficulties. As a consequence, the operation of the hydraulic structures is influenced by the sediment deposition in the canals. This concerns especially movable weirs, which are sensitive to the fluctuation of the water levels. Due to this, it is becoming more difficult to maintain the intended discharge into the minor canals (Osman et al., 2011).

3. A Tale of Two Gezira's

In this chapter, the MASSCOTE framework is implemented in analyzing the different components of the Gezira scheme. From searching in literature, official documents, and data, it is found that there are two Gezira's: a Gezira appearing from official documents and a Gezira appearing from actual data. This was seen clearly in most of the analysis steps. There are differences in terms of farming (crops, water needs, time of irrigation), in terms of canal system (operation, maintenance, flows), and in terms of decisions (who decides on what). Therefore, it was needed to apply MASSCOTE to the two versions of the Gezira and with more focus on the canal system.

MASSCOTE stands for Mapping System and Services for Canal Operation Techniques. It is a step-by-step framework established by FAO-WATER, as an approach that is developed to evaluate the performance of irrigation systems in order to provide modernization plans for them. It analyzes the different components of the system, including physical, institutional, and managerial aspects. The core of the MASSCOTE framework is the canals operation. As stated by FAO-WATER, "Canals reflect the existing performance and express the constraints, limits and opportunities of the management". It also focuses on the services delivered to end users, farmers, as they are the main benefiting part of the scheme.

3.1. Gezira appearing from the official documents

3.1.1. Step 1: Rapid Appraisal Procedure

Physical Infrastructure

The physical infrastructure component represents the main pillar in the productivity process in the Gezira scheme. It acts as the backbone of the water delivery service. The irrigation in the Gezira is not continuous throughout the whole year. As stated before there are two cropping seasons, summer and winter. In the first period of the summer season (May to September), the scheme depends largely on rainfall water, and irrigation is considered to be supplementary. Another reason for not irrigating in these months, is the huge amounts of sediments coming from the Blue Nile river, that may enter the system (El Monshid et al., 1997). In the winter season (October to March), the crops depend mainly on water coming from irrigation. The irrigation water supplied to the Gezira comes from Sennar dam through two main canals: Gezira Main Canal and Managil Main Canal meeting together at a junction called Kilo 57 (57 km from Sennar Dam). At this junction, the irrigation water flow is measured by using the head works, which distribute water to all parts of the scheme (Osman, 2015).

There are four levels of water distribution and delivery system in the Gezira scheme. The first level consists of two main canals coming from Sennar dam. The Gezira Main Canal (design capacity of 168 m^3/s) and Managil Main Canal (design capacity of 186 m^3/s). Then comes the second level which consists of 11 branch canals with a total length of 651 km, with conveyance capacities ranging from 25 to 120 m^3/s. The third level is 107 major canals of total length 1,652 km with a carrying capacity ranging from 1.5 to 15 m^3/s. Then, the fourth level is the set of 1,498 minor canals with a total length of 8,119 km with delivery capacities ranging from 0.5 to 1.5 m^3/s (Plusquellec, 1990). All canals are divided into reaches by cross regulators, which are considered as control points for the off-taking canals. The main, branch and major canals are designed as regime conveyance channels, while the minor canals are designed for storing water continuously flowing from the major canals at night. The water deliveries from the minor canals go to Abu Ishreen through field outlet pipes (FOP). The command area of each minor canal is divided into groups of fields called Nimras, arranged parallel to each other and irrigated by water courses called Abu Ishreens. The Nimra is about 37.8 ha (90 feddan). The distance between Abu Ishreen canals is 292 m. The water is diverted to lateral courses called Abu Sitta, that deliver the water to the fields/farms. Figure 3 illustrates a schematic drawing of the irrigation system in the Gezira scheme. Currently, there are 29,000 water courses called "Abu Ishreen" (Abu XX) with a total length of 40,000 km with 116 l/s capacity, and 350,000 field channels called "Abu Sitta" (Abu VI) with a total length of 100,000 km with 50 l/s capacity (Gismallah, 2011).

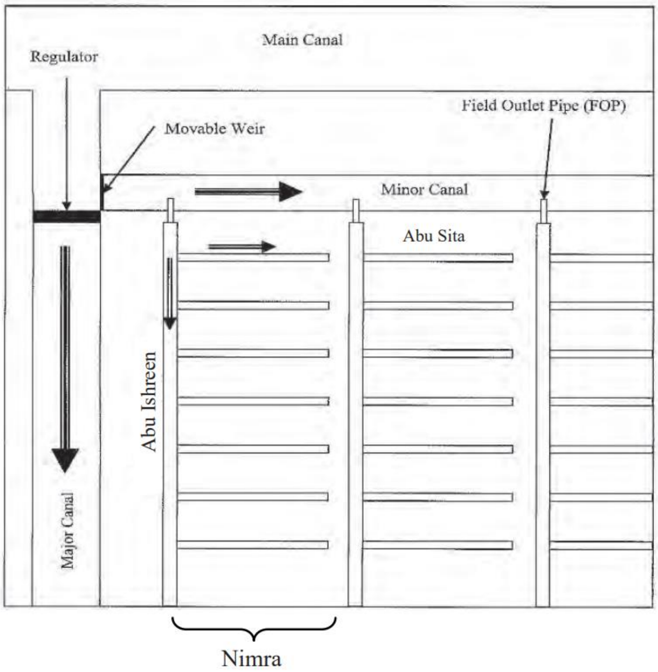


Figure 3. Layout of the distribution system in Gezira Scheme (Osman, 2015)

Project Management:

The Gezira Scheme is currently operated under the combined management of the Ministry of Irrigation and Water Resources (MoIWR) and the Sudan Gezira Board (SGB) as a government enterprise.

Before 1950 the management was divided between the Sudan Plantation Syndicate and the Ministry of Irrigation and Water Resources. After 1950, the management of the Gezira has become a joint management between MoIWR and SGB (Bashier et al., 2015). The latter came as a replacement for the SPS. MoIWR and the SGB work closely together and their roles integrate each other in the management of the scheme. The MoIWR has the responsibility of operation and maintenance of the Sennar Dam and the main, major and minor canals since the construction of the scheme in 1925. It is responsible of delivering water according to the required indent up to the field outlet pipes of the Abu Ishreens, while the SGD is responsible for agricultural management, consisting of maintenance and operation on the field levels, which includes the FOP gates, Abu Ishreens, and Abu Sittas. It also determines crop rotations and prepares the land for cotton. It is also responsible for application of fertilizer, pesticides, and seed propagation. The SGB works in coordination with other institutes, like the Agricultural Research Corporation (ARC), the Sudan Cotton Company (SCC), and the Gezira State Government (Abdelhdi et al., 2015).

In 2005, the SGB established a new act for managing the scheme, 'The Gezira Scheme Act of 2005', and attempted to activate this act in 2010. The SGB was assigned all responsibilities for the operation and maintenance of the canals. According to the 2005 act, SGB has established 1700 water user groups according to the number of the minor canals, which were named Water Users Associations (WUA)s. The farmers were participating in the operation and maintenance of the minors and the field canals. One of the WUAs responsibilities is to collect irrigation fees according to the cropped area. The share of the SGB is 20% of the collected fees, while the other expenditures of the maintenance activities are met by the WUA (Elshaikh et al., 2018).

Farmers do not own their lands; they are considered as tenants through what is called the Tenancy System that is implemented in the Gezira Scheme. The total area is divided between 102,000 tenancies with an average of about 20 feddan. They are responsible for land preparation for crops other than cotton (Ibrahim et al., 2000).

3.1.2. Step 2: System Capacity and Functionality

Design of Irrigation Canals

The regime method has been adopted as the base of the design of stable (non-silting/non scouring) canals in Sudan. It consists of empirical equations, based on observations from canals and rivers that have achieved dynamic stability. This can only occur when the sediment input to the canal matches the average sediment transport capacity. The regime theory was developed by Kennedy (1895) to aid the design of major irrigation systems in India, and followed up upon by Lindley (1919). Lacey (1930) published the most popular set of equations. The equations were based on data from three canal systems of the Indian Sub-continent. They specify the cross-section and slope of regime canals from the incoming discharge and a representative bed material size. They are, with minor changes in the coefficients and some redefinition of the silt factor, still widely used (Osman, 2015).

The main, branch and major canals in the Gezira Scheme were designed as regime conveyance canals. From Gismalla & Fadul (2011) the general equations of the regime method are:

$$P = K_p\, Q^{1/2}$$

$$A = K_a\, Q^{5/6}$$

$$S_o = K_s\, Q^{-1/6}$$

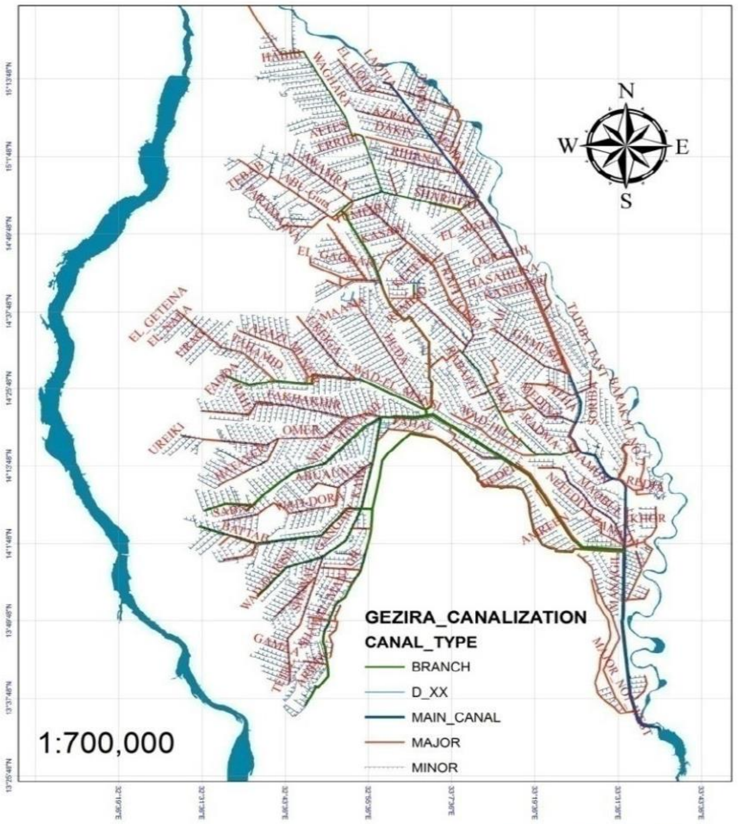
Where:
P = wetted perimeter (m)
Q = discharge (m^3/s)
A = cross-sectional area (m^2)
S_o = bed slope (cm/km)
K_p, K_a, K_s = constants (-)

The discharge in the formula was taken as the average maximum authorized discharge. The constants depend on the nature and magnitude of the sediment transported as well as the materials forming the canal bed and banks. The minor canals were designed, based on the Manning equation, for night storage, with water flowing continuously from the majors at night (Plusquellec, 1990).

The canals are designed to irrigate a certain percentage of the irrigated areas. For example, in the Gezira only 50% could be irrigated in a season, while in Managil up to 66% could be irrigated. Any addition to these percentages will lead to water fluctuations in the system.

Canalization system

The irrigation network in Gezira Scheme is considered to be one of the most complicated networks being operated under surface gravity irrigation systems. It consists of main and branch canals that supply water to the major canals. These canals are all designed as conveyance canals. Then the major canals deliver water to the minor canals. Figure 4 shows the layout of the irrigation system in Gezira and Managil Scheme. The total number of Abu Sittas has been increased since more canals have been excavated (In the past the distance between Abu Sittas was 150 m but now it is 30 m).



Mohanad Osman Mustafa
HRS -MOIWR

Figure 4. Layout of the distribution system in the Gezira Scheme (Hydraulics Research Center - Sudan)

Downstream of the first common cross-regulator at km 57, the main canals are divided into reaches, which vary in length from 5 km to 22 km, by further cross-regulators. These regulators are the control points for the branch and major distributary canal offtakes. The branch canals are similarly divided into reaches by cross-regulators and major distributary canals are grouped at these regulators. Then, major canals are divided into reaches of around 3 km, and minor canal offtakes are generally grouped at the cross-regulators as well. There is normally no irrigation offtake direct from the main canals, branch canals or major canals. The carrying capacity of the conveyance system (0.39 l/s/ha) can meet the maximum demand on the system at full rotational cropping of 75% (Plusquellec, 1990).

Table 4. Canalization characteristics of the Gezira Scheme (Ibrahim et al., 2000)

Canal	**Number**	**Capacity (m^3/s)**	**Average width (m)**	**Length (km)**
Main	2	354	50	261
Branch	11	25-120	30	651
Major	107	1.2-15	20	1,650
Minor	1,700	0.5-1.5	6	8,120
Abu Ishreen	29,000	0.116	1	40,000
Abu Sitta	350,000	0.05	0.5	100,000

Minor Canals

The minor canals are a key feature of the Gezira irrigation system. They are over dimensioned in relation to the flow they have to convey, especially in the downstream reaches, since they have been designed to act as night storage canals (Gismalla & Fadul, 2011). The total length of a minor canal can be as much as 20 km. Each minor is divided into reaches with a length varying from 1 to 4 km depending on the slope of the land. The reaches are separated by night-storage regulators consisting of a brickwork well and sluice gate or, in the lower reaches, by a gated pipe. The canal banks are set further apart than what would be required for carrying the required flows. At intervals of 292 m along the minor canal, field outlet concrete pipes take off at right angles, each feeding a 90 feddan field called Nimra. These pipes are 12 meters long and 0.35 m diameter, they are buried at least 60 cm below the service road of the minor canals (Gismalla & Fadul, 2011).

Night Storage System

The Gezira Scheme was originally designed to be operated as a continuous irrigation system. Due to practical difficulties in irrigation at night, such as unavailability of staff and farmers, the system of irrigation at the level of minor canals was changed to be operated on what is called the night storage system in the early 1930s (Ibrahim et al., 2000). The types of night storage weirs (NSW) used as cross structures are rectangular and circular weirs. They contain gates treated as an orifice. These gates are closed when the night storage system is in use, during night, and only opened at emergency. The idea behind the night storage system is to store water during the night by closing the gates of the field outlet pipes of the Abu Ishreen canals and the gates of the cross structures along the minor canal at 6:00 pm, and reopen them at 6:00 am. At night, the water level increases gradually along the reaches to about 20 cm above the full supply level (maximum water level) and flows from upstream to the next downstream reach over the crest of the weir to give better command for irrigation during the day (Mohamed et al., 2010).

Field Outlet Valves

The field outlet valves discharging into the Abu Ishreen through field outlet pipes (FOP) consist of a chopper-type valve. The flow is controlled by rotating the chopper gate around a hinge pin.

Drainage System

The original design of the scheme minimizes the importance of designing a complete drainage system. The main reason was due to the characteristics of the soil of the scheme and the absence of high ground water table (Al Zayed et al., 2015). The need for drainage was only for discharging rainfall flows and excess irrigation waters.

There are three types of drains in the Gezira Scheme; protective drains, collective drains and escapes. The protective drains are designed to protect the agricultural areas from water coming from outside the scheme, especially floods water coming from hills, for example the Managil hill. The collective drains are designed to be within the system. It consists of minor drains that transport water into major drains, where the latter delivers water into the nearest natural drain. The minor drains are parallel to the minor canals and have a total length of 6,000 km. The major canals have a total length of 1,500 km (Osman, 2015). There are no drains parallel to the Abu Ishreens in order to discharge water from fields.

The escapes are usually connected to the main canals, in order to protect the canal from failure when there is surplus of water due to rainfall. The main canal is provided with three escape drains. The first two are designed to discharge 20 m^3/s, and the third has a capacity of 16 m^3/s (Elshaikh, 2020).

3.1.3. Step 3 -4: System Sensitivity & Mapping Perturbations

Hydraulic structures

The hydraulic control structures were designed to maintain a constant upstream level and discharge. They are controlled manually on the supervision of attending staff. The two main classes of regulator gates in use are the vertical lifting sluice gate and the movable weir. There are a number of different types of sluice gate (gantry operated sluice gates, rack and worm gates, roller sluice gates). The system of water control throughout the distribution system relies on a knowledge of the discharge characteristics of the regulator gates. Table 5 describes the different types of hydraulic structures in Gezira Scheme.

Table 5. Different types of structures in the irrigation network of the Gezira Scheme (Elshaikh, 2018)

Type of structures	Range of size (m)	Total number	Function
Moveable weir	0.30 - 3.00	885	Head and cross regulator
Roller sluice gate	1.00 - 4.00	137	Head and cross regulator
Well head regulator	0.35 - 1.24	420	Head regulator
Well head regulator	0.35 - 1.24	1707	Cross structure
Night storage weir (circular/rectangular)	0.24 - 1.24	1426	Cross structure
Field outlet pipe (FOP)	0.35	28910	Head regulator

Sluice Gate Regulators

The sluice gate regulators regulate the flow at main, branch canals. These types of regulators are preferable for discharge regulation as canal head regulators. The flow through sluice gates is estimated from calibration charts, which requires readings of gate opening, upstream and downstream levels (Johnstone, 2000). The basic formula for submerged flow is as follows;

$$Q = C_d A \sqrt{H}$$

Where:
Q = discharge (m^3/s)
C_d = discharge coefficient (-)
A = gates opening (m^2)
H = head difference between upstream and downstream (m)

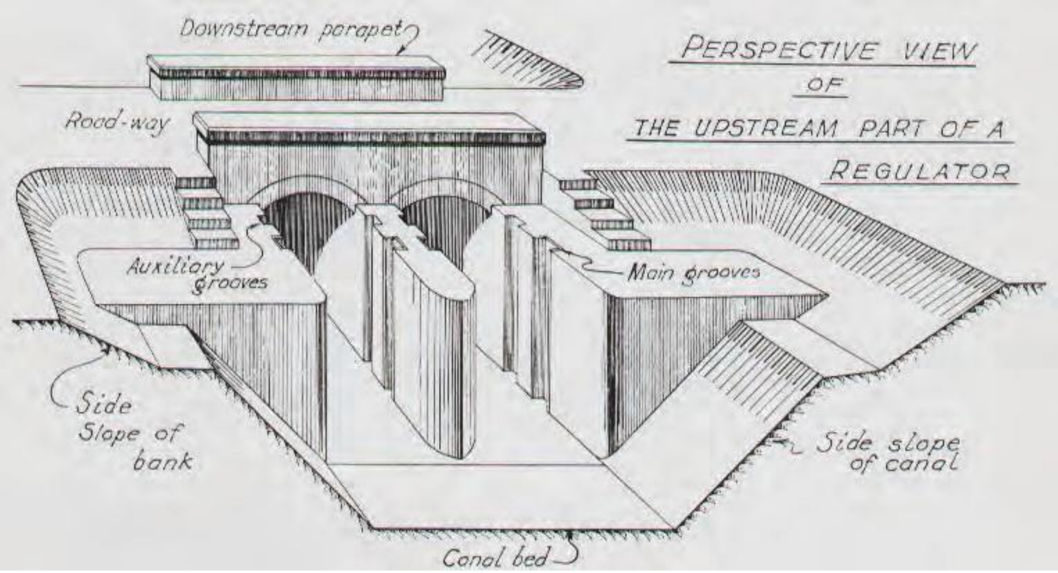


Figure 5. Drawing of a head regulator from the design sheets used in the Gezira Scheme (MoIWR, Design sheet file)

Movable weirs

Movable weirs are useful for regulation, since the impacts of change in the crest position are more understood than for gates (Clemmens, 2006). The weir consists of a round-crested movable gate with guiding grooves and a self-sustaining hand gear for raising and lowering it. The cylindrical crest is horizontal, perpendicular to the flow direction as illustrated in Figure 6. A staff gauge is attached to the weir at 0.75 of the maximum upstream water depth.

Table 6 presents the two types of movable weirs in Gezira Scheme; movable weir series-1 (MW-I) and series-II (MW-II). The weirs are designed to pass the maximum full supply level (FSL) discharge and maximum head over the crest level. The flow and water levels upstream are not affected by changing the flow condition downstream, whereas in drowned or submerged structures they have an effect.

Table 6. Characteristics of the movable weirs (MoIWR, Design sheet file)

Description	**MW-I**	**MW-II**
Range of discharge (m^3/s)	< 1	1-5
Travel distance (m)	0.56	0.84
Floor level to crest level (full open) (m)	0.8	1.1
Maximum width (m)	1.3	3
Maximum depth (m)	0.6	0.8
FSL to floor level (m)	1.3	1.9
Discharge coefficient (-)	2.18	2.3
Overall depth of wall	1.5	2.2

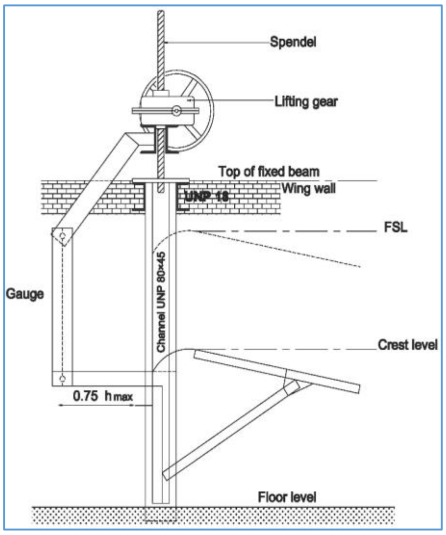


Figure 6. Movable weir in Gezira Scheme (Aalbers, 2012)

3.1.4. Step 5: Water Networking and Accounting

There are three main methods of operating irrigation canals; on demand, continuous and rotational. The rotational water distribution method is a common well known practice throughout the world (Mohamed et al, 2010). The irrigation is delivered into field in a rotational basis, where a fixed frequency, and constant depth policy is followed. With this method, the operation schedule of the water distribution system is known by calculating the irrigated area of each supply unit (canals). Once the irrigated area is known, the irrigation scheduling is prepared and executed throughout the season. This approach has been implemented in the Gezira through what is called Water Duty System. There are some remarks about this method. All diverse crops in this method are treated to have the same crop water requirements (evapotranspiration). Also, the CWR is the same throughout the different stages of the crops growth. Therefore, it only depends on the irrigated area regardless of the crop type, growth stage, or weather conditions. For the Gezira case, it is estimated that the requirements of all crops are at 30 m3/feddan/day inclusive of field losses at the head of the Abu Ishreen (Ahmed, 2009). This is equivalent to 420 m3/feddan per fortnight (100 mm application depth). The quantity to be applied to a 90 feddan Nimra will then be in the order of 5,000 m^3/12 hours for an open FOP, based on a 7-day application. For this discharge, (116 l/s), the head difference in the FOP should be 0.15 m (Mohamed et al. 2010).

However, in recent decades, this method of fixed frequency and fixed depth has been upgraded into fixed frequency, but variable depth. In this approach, the irrigation water requirement depends on the soil-crop-climate conditions. This is known in the Gezira by the Farbrother approach, with the actual CWR depending on the crop factors generated by Farbrother (1974). More details are provided in appendix B.

The cycle of water management in the Gezira starts from the field and ends at Sennar dam and the water delivery is vice versa. The Block Inspector makes up a schedule of irrigating the Nimras on each minor canal, where each Nimra being fed by one Abu Ishreen. He is responsible of determining the irrigated area in his block. The blocks are land units varying in size depending on topographical and geographical factors, the average area of a block is about 20,000 feddan (Plusquellec, 1990). Eventually, all block inspectors in one sub-division pass their areas to the sub-division engineer. When the MoIWR Sub-Divisional Engineer has received the irrigated area for all the minors in his sub-division, he sums them up to give the required discharge at each control point on the system in his Sub-Division and to give the total required to the next Sub-Division upstream. The indent is passed from downstream sub-division to upstream sub-divisions with corrections for canal conveyance losses, until the total is passed to the head works of Sennar dam, where the gates are adjusted (if needed) to give the discharge required (Woldegebriel, 2011). As the revised discharged becomes available, all other regulators down streams are adjusted in turn. This indenting system can be further understood by viewing the layout of the sub-divisions provided in section 3.1.7, with the arrows in the figure showing the flow of orders from downstream (North) to upstream (South).

Field Irrigation System

The field irrigation system is designed to serve the Nimras (90 feddan fields). Each Nimra is divided into eighteen sections of 5 feddan plots (called hawasha), watered by secondary water courses, called Abu Sitta (taking off from Abu Ishreen). A Nimra is normally planted with one crop (cotton, wheat) or divided between simultaneous crops (groundnut, sorghum). The Abu Ishreen had originally a design bed width of 1.00 m and a depth of 0.40 m and a design command of about 0.20 m (Aalbers, 2012). The Abu Ishreen is nowadays rebuilt by a special ditcher pulled by a crawler tractor, and its new section is dictated by the plant used for construction. Its theoretical capacity is 116 l/s (0.115 m^3/s). In the standard field layout, the hawasha is further divided into fourteen angayas by small ditches. The angayas, in turn, were divided into 10 smaller basins called hods. This subdivision has been abandoned, as it was demanding for the tenants in time and energy. Irrigation water distributed from the Abu Sitta is now distributed to the angayas until there is free standing water throughout the field (Osman, 2015).

Table 17 in the appendix shows an example of irrigation scheduling in Toman Minor canal in September 2012. The irrigation period is assigned to be seven days and the irrigation interval is determined as 14 days.

3.1.5. Step 6: Cost and Operation

The MoIWR has a fixed budget from the government towards operation and maintenance. The budgets for the Gezira scheme is broken down in three main components (Plusquellec, 1990);

- Salaries and allowances of the staff involved in field operation, plus a percentage of the salaries of the staff at the Wad Madani Headquarters.
- Operation and maintenance expenses including silt and weed clearance, repair of structures, expenses for Wad Madani and El Gorashi Workshops, Sennar dam, and administration expenditures.
- Replacement of equipment machinery and major maintenance (replacement of Sennar dam gates), procurement of vehicles, and capital cost recovery.

Salaries and personnel allowances represent only 10 % of the total Operation and Management expenditures, which is very low compared to other countries. The Joint Account system was in use in most irrigation schemes in the Sudan until 1980. Under this system, the expenditures incurred by the Agricultural Corporations, such as the Sudan Gezira Board, were deducted from the total revenue received from cotton sales. The net revenues from cotton were then distributed between the government, the corporation, and the tenants in agreed proportions. The tenants' share was then divided by the total scheme production of seed cotton to arrive at a price per kantar of seed cotton payable to each tenant. Under this system, cotton bears the burden of other crops in the rotation, resulting in a disinterest of the tenants (which grow cotton because they must), and a sharp decline in cotton productivity in the mid-1970s. In 1980, the Joint Account system was abandoned and replaced by the individual account system. The tenants are charged for each input for each industrial crop, and they receive the net revenue based on their productivity. In 1981, the new method to be used in settling land and water charges was established to recover administration and operating costs of both SGB and MoIWR, their capital replacements and new investment costs. These costs amounted to about 28.4 million dollars in 1981-82 (Woldegebriel, 2011).

3.1.6. Step 7: Service to Users

Water delivery service

As indicated previously, the water orders (demands) are generated in an upward direction, while the water delivery is vice versa in a downward direction. In each section, the demand for downstream is released first, then the remaining water is assigned to the section. On field level, the irrigation water entering the Abu Ishreen is distributed over the Nimra in one week. The first upstream hawashas are irrigated within 3 days, while the remaining 5 downstream irrigate in 4 days.

The role of the MoIWR is confined to ensure the delivery of water into the minor heads as indented by the block inspectors, provided that the water demands are within the canal carrying capacities. The system demands the closest possible contact between the SGB inspectors and the operational engineers, who control the sources of supply. The sub-division engineers are responsible of renewing the indent on a daily basis during the first stages of the crops growth in the beginning of the irrigation season, in early June to the mid-July. Since this is the rainy season, the indents are renewed daily with a second indent in the evening, called rain-cut indent in case of heavy rain. After the rainy season, the water indents are passed on a weekly basis. From March to the end of May, water is released only to meet the requirements of water supply and irrigation for vegetables (Adam, 2005).

3.1.7. Step 8: Management Units

The Headquarters of MoIWR for operating and maintaining the Gezira scheme is located at Wad Madani. MoIWR is organized into two Directorates, one for the Main Gezira and the other one for the Managil Extension, located at Gorashi. The two directorates are divided into four Divisions, and these Divisions are divided into 23 subdivisions under the control of an Assistant Divisional Engineer (ADE) (see figures 7 and 8). The Subdivisions are further divided into 72 sections, each run by an Assistant Engineer (MoIWR).

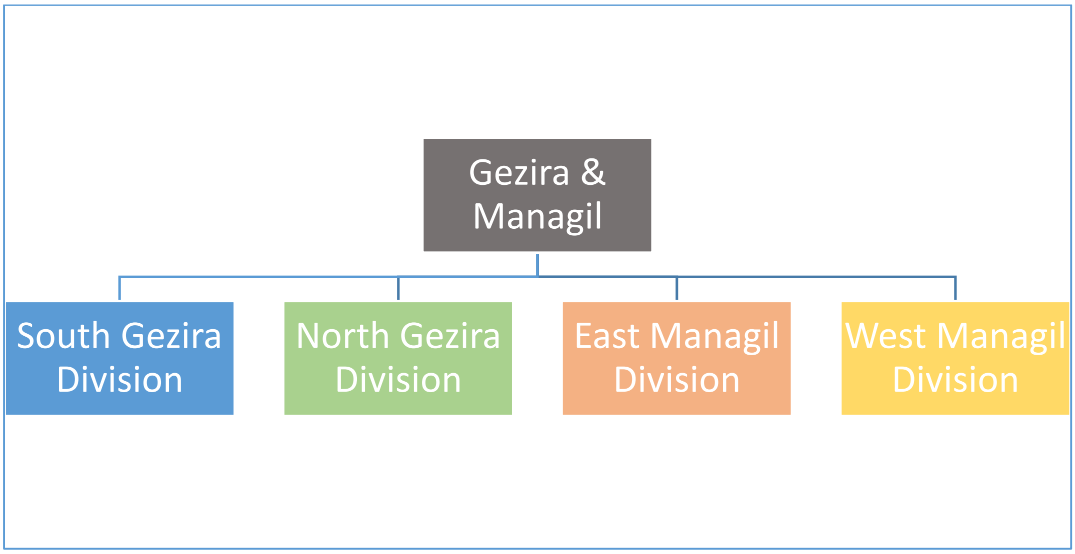


Figure 7. Division of Gezira and Managil

South Gezira Division: it has area of 457,152 feddan, and consists of 6 sub divisions and 15 blocks. The head offices are located in Wad Madani.
North Gezira Division: it has area of 764,199 feddan, and consists of 7 sub divisions and 24 blocks. The head offices are located in Abu Ushar.
East Managil Division: it has area of 433,929 feddan, and consists of 5 sub divisions and 15 blocks. The head offices are located in 24 Qurashi.
West Managil Division: it has area of 569,086 feddan, and consists of 5 sub divisions and 18 blocks. The head offices are located in 24 Qurashi as well.

Figure 8 below illustrates all the irrigation sub-divisions, where the color indicates which division it belongs to with respect to figure 7. The figure also shows the flow of water demands (indenting) from far up north (downstream) to the first subdivision (upstream, in the south).

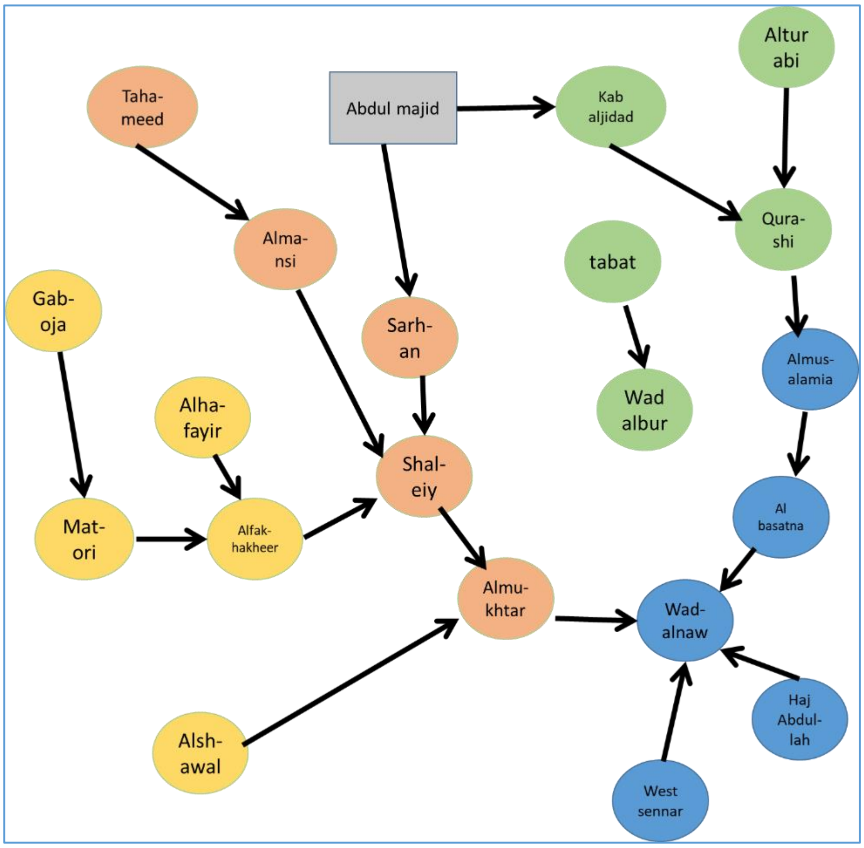


Figure 8. Management units of Gezira and Managil

3.2. Gezira appearing from the data

Rapid Appraisal Procedure

Physical Infrastructure

The hydraulic infrastructure of the system has worsened overall. As stated by the governor of the scheme in 2020, 85% of the hydraulic structures are destroyed, while the canalization system is far from the design status, due to siltation and over-digging (MoIWR). The pictures in figure 9 below illustrate some of the examples of damaged structures.

Figure 9. pictures of damaged and non functional NSW (Woldegebriel, 2011)

Regarding the canals status, figure 10 below illustrates the cross-section change due to siltation and over digging in Toman minor canal (Osman, 2015). The change in cross-section with respect to the design is clearly visible. The change is present in different locations in the canal reaches. Concerning the left cross-section, we can see the influence of siltation, resulting in an increment of bed level by nearly 1.5 m. In the right cross-section, both siltation and over-digging are present. The over-digging has widened the cross section.

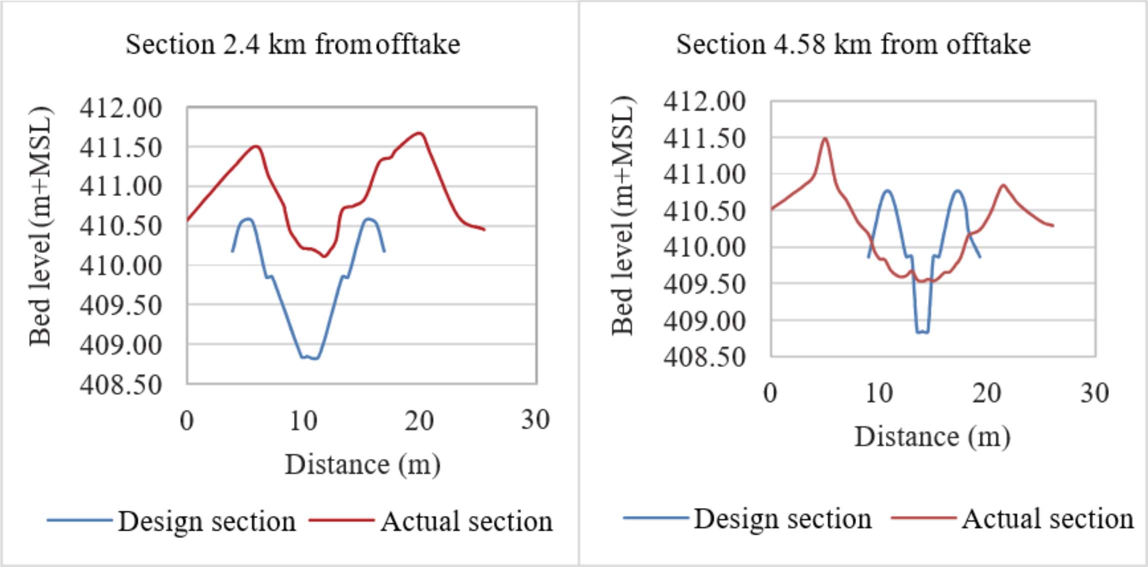


Figure 10. Actual and design cross-section at various locations in Toman Minor Canal (Osman, 2015)

System Sensitivity and Mapping Perturbations

One of the main issues in Gezira's distribution system is siltation, especially in the minor canals. As they are used as night storage systems, they tend to trap the silt released into the system. In some minor canals, only little water reaches the tail end, where some numbers are dried out (Gismalla, 2009)

Due to deterioration in the status of movable weirs as shown in the previous section, in addition to their sensitivity to the fluctuating water levels in the major canals, it became difficult to maintain the indented discharge into the minor canals. Some of the FOPs, NSWs, Minor offtakes are totally destroyed or stolen. Now, valves have been replaced by oil drum bottoms, bags or other local materials. In addition, there is no calibration of the gates, there is no relation between the MoIWR opening gate records and the actual gate opening (HRC).

Figure 11. Right, farmers closing a NSW with Iron sheet, Left, Missing Field Outlet pipes (Woldegebriel, 2011).

The issue of night storage versus continuous irrigation is clearly the most complex one in the operation of the Gezira system. It has been suggested to replace the night storage system by continuous 24-hour irrigation and to narrow the minor canals. The advantages advocated to support this approach are that flow velocities would be increased, causing reduction in the volumes of silt now trapped in the minor canals. The area requiring weed clearance would be reduced. It was also argued that, since continuous flow irrigation is already widely practiced in Gezira, the changes in the rules of irrigation should not be a critical social issue. It implies the elimination of a key feature of the design of the Gezira irrigation system (Mohamed et al., 2010 & Babiker et al., 2017). Only the downstream effects of this change, i.e., on field water applications and social and economic consequences on maintenance costs, have been considered so far. A fundamental aspect seems to have been overlooked: the night storage concept plays a major role in the operation of the Gezira scheme. The inevitable deviations between demand and supply of water are stored or withdrawn from the minor canals. The minor canals play a major role for the successful operation of the Gezira, despite the absence of staff gauges, the inaccuracy of adjustments of gate regulators and movable weirs. It is also argued that the shift from night storage to continuous irrigation by narrowing the canals will not solve the problem of siltation in the minor canals, it may only transfer the silt to another location in the minor canals. An answer to the issue itself of continuous versus night storage irrigation may be found in a future modernization of the operation of the main branch and major canals.

Water Networking and accounting

The original night storage system turned into a continuous, 24-hour irrigation water delivery to the fields, which is not supervised by the tenants during the night. This has resulted in longer irrigation periods and less discharge entering the fields. The irrigation engineers complain that they are no longer able to maintain the traditional supply levels that are expected. Due to the 24-hour continuous operation, the average discharge through the FOP have decreased from 116 l/s to 40 – 50 l/s (Ibrahim et al., 2000). This also resulted in long periods of water standing in the fields, which leads to waterlogging, hence reduced oxygen for crop growth and nutrient uptake. As an end result, this contributes to lower crop productivity.

Figure 12. Water standing on the field (Woldegebriel, 2011)

On the drainage side, the Gezira scheme is characterized by a very limited capacity to remove surplus water. Very large areas on the border of the scheme have no escape possibility at all. The total escape capacity is 67 m3/s (Elshaikh, 2020), which is less than 20% of the capacity of the main canals, and is intended primarily to allow for emergency spillage due to sudden decreases in irrigation demand following rainfall. As a result of the low escape capacity, combined with the long length of supply canals, farmers are often required to continue to take water into their fields for some time, even when these are already flooded by heavy rain (Osman, 2015).

Cost and Operation

In earlier years, when the irrigation canals were in better condition, removal of 5 to 7 Mm^3 of sediment annually was considered to be satisfactory (Plusquellec, 1990). In recent years, the canal condition has deteriorated to an extent that the canals failed to satisfy the crop water requirements (Gismalla et al., 2009). In 1999, a substantial canal desilting program was carried out. According to the records, 41.0 Mm^3 of sediment was removed from the Gezira Scheme canal systems. This is likely to be an over-estimation of the sediment removal due to the over-digging of the canals. The total cost was US$ 26 million (Osman, 2015). Excessive sediment removal in 1999 caused over-digging to most of the Gezira canal system. There is a variation of the sediment load entering the Gezira Main Canal over the years, but the general trend is an increasing one. The cost of sediment removal has become a major item in the MoIWR annual budget. Most of the canal cross-sections are over-dug and this improper excavation even leads to changes in the canal beds and physical and hydraulic properties of the canals, which accelerates the rate of sediment deposition. Besides that, the clearance work is not according to the actual requirements, but depends on the availability of budget, machines, and priorities – which are given to the worst conditions.

Service to Users

Recently, with intensification resulting in larger cropped areas, more water and time are required to meet the crop demand. As a result, less time for irrigation is available to each tenant. Therefore, tenants started to leave field outlet gates open for 24 hours, without supervision. In this way, the continuous flow in the minor canals became dominant in the scheme, without any attendance by the farmers at night. As a consequence of the practice of this 24-hour flow, and the higher number of field outlet pipes that are open at one time, the discharge through the pipes decreased. The well-defined daily pattern, which characterized the old night storage use of the minors, has been replaced by a much more irregular pattern. The water levels in the minor canals can generally not be maintained at FSL. The command over the Nimra is consequently reduced and the land takes a longer period to be irrigated (Umolu, 2015). The openings of outlets depend now on the tenants' judgment of the requirements of their crops. Block inspectors rarely interfere in the routine opening and closing of outlets. Unfortunately, several farmers lack awareness about irrigation water application. Conditions have deteriorated so much in some areas that lands are taken out of production (Adeeb, 2006).

Although it is forbidden to take water directly from the larger canals, yet some farmers practices tend to install pumps that pump water directly to their fields (Elshaikh, 2020). This act is considered illegal according to the law of irrigation and drainage of the Gezira irrigation scheme, but still it is found to be present in many cases. This act is known as Nakoosi in the Gezira scheme. The figures below show some examples of Nakoosi, which seems to be widely spread in the Gezira.

Figure 13. Farmers using pumps to pump water over the canal (Osman, 2015)

Management Units

The tenant lost confidence in the timely operation of the system and, to some extent, took over the management of the minor canals. They feel that, although they pay for maintenance, the work is not fully carried out by the authorities. The farmers are not satisfied with the overall management and maintenance of the scheme, while the authorities are not satisfied with the tenants' water use (Eldaw, 2004).

Large parts of the MoIWR work force are not skilled enough to operate the regulators manually. There is a miss-recording of the data by the MoIWR and the SGB, which makes it even harder to assess the real situation of the system (Eldaw, 2004) . For example, the areas delivered by the block inspectors to the sub-division engineer appear to be exceeding the actual area, in order to receive more irrigation water. On the other side, the MoIWR also reduces the amount of water delivered and claims to have met the required indents. According to the World bank (1990), in some cases, the SGB has submitted areas that are 44% higher than the actual, while the MoIWR released water that met 78% of the indented delivery request.

Water Budget

In order to evaluate the current performance and to have a better understanding of the actual operation of the minor canals served by Zananda major canal, a simple water budget analysis was carried out. The measured data was obtained from a previous study, Osman 2015, University of Khartoum, Sudan. In the analysis, the actual crop water requirements of each minor canal, in the summer season of 2012, was compared to the actual water released, which was measured at the offtake of each minor canal. For all minor canals, there was no irrigation during the period of August. Water demands are considered to be compensated by rainfall. We can notice the fluctuation of the recorded released discharges with respect to the crop water requirement in figures 15 to 21. The locations of the minor canals are shown in figure 14 below.

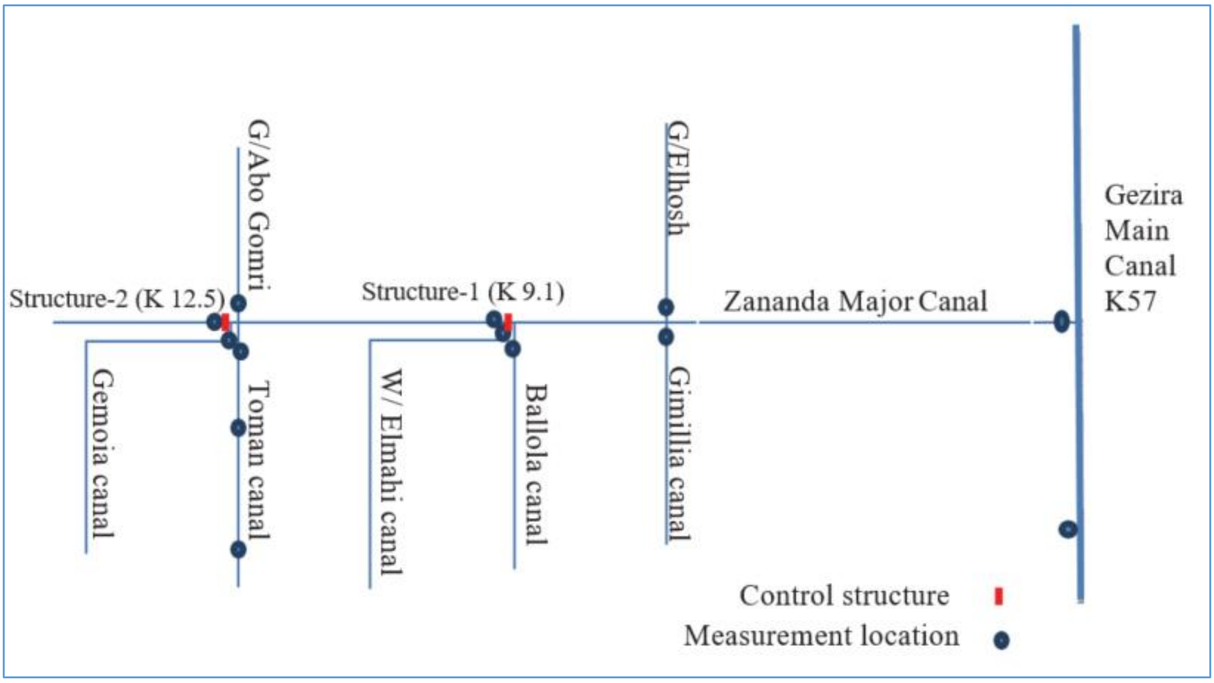


Figure 14. Location of mnior canals served by Zananda Major Canal (Osman, 2015)

The general observation from the graphs shown below is that the recorded releases do not match the actual CWR, not even an overall general trend is noticed. In addition, there are rather huge fluctuations in the releases.

For G/Elhoush minor canal, the release was higher than the CWR during the period of July, and lower during for the rest of the season. The same trend is present in Ballola Minor canal: excess of releases in the beginning of the season and lower discharges after the rainfall period. For Gimillia and A/Gomri minor canals, we can find that there is huge excess of release compared to the CWR at the end of the month September.

For Gemoia and Toman minor canals, the released discharges are recorded to be higher in both periods, before and after the rainy season.

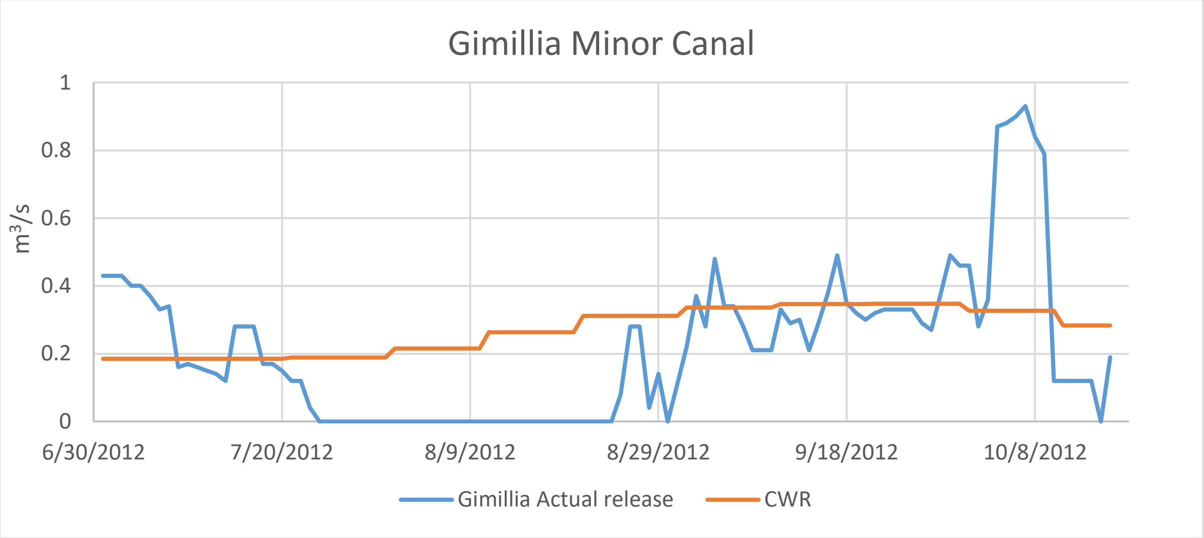


Figure 15. Gimillia actual Release versus actual crop water requirement

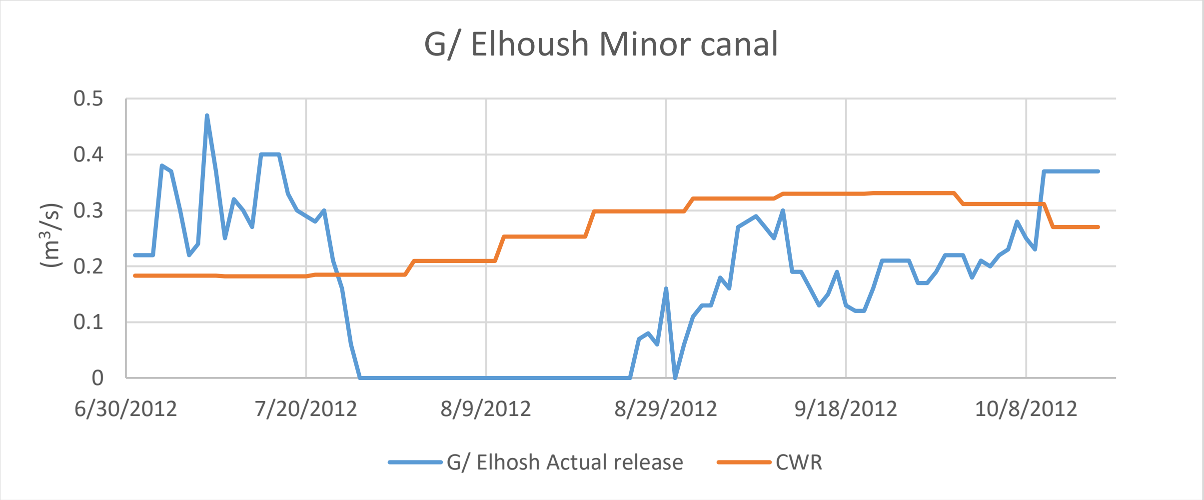


Figure 16. G/ Elhoush actual Release versus actual crop water requirement

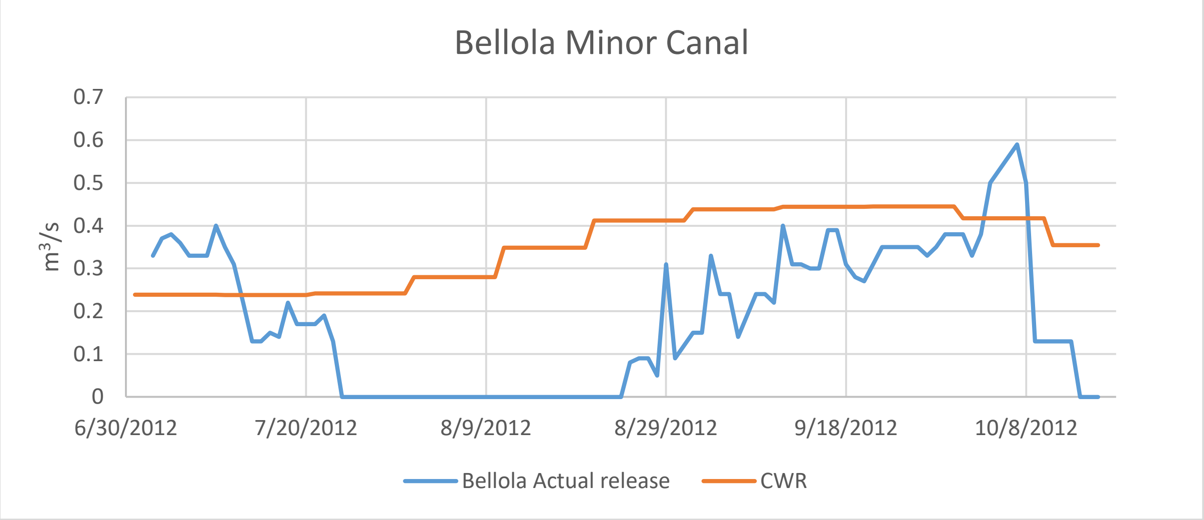


Figure 17. Ballola actual Release versus actual crop water requirement

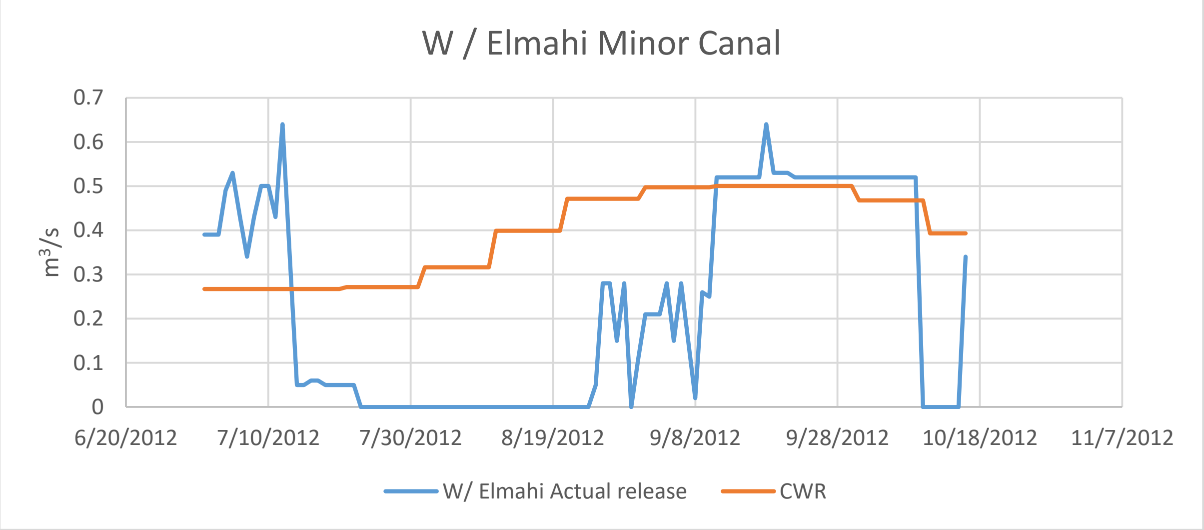


Figure 18. W/Elmahi actual Release versus actual crop water requirement

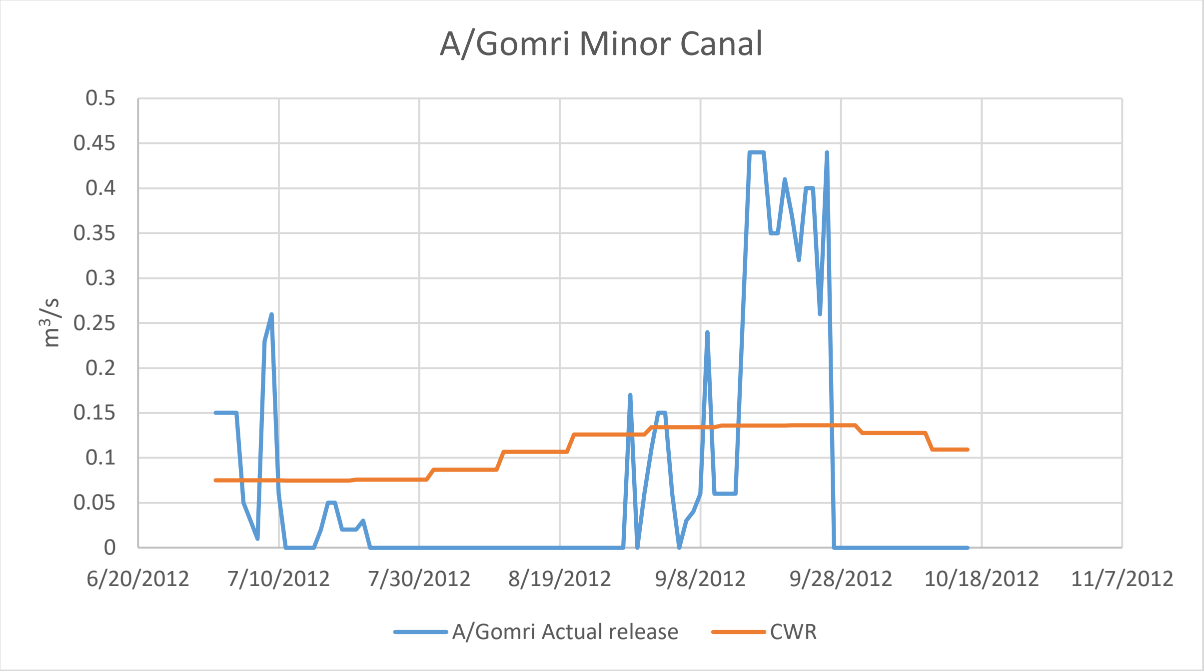


Figure 19. A/Gomri actual Release versus actual crop water requirement

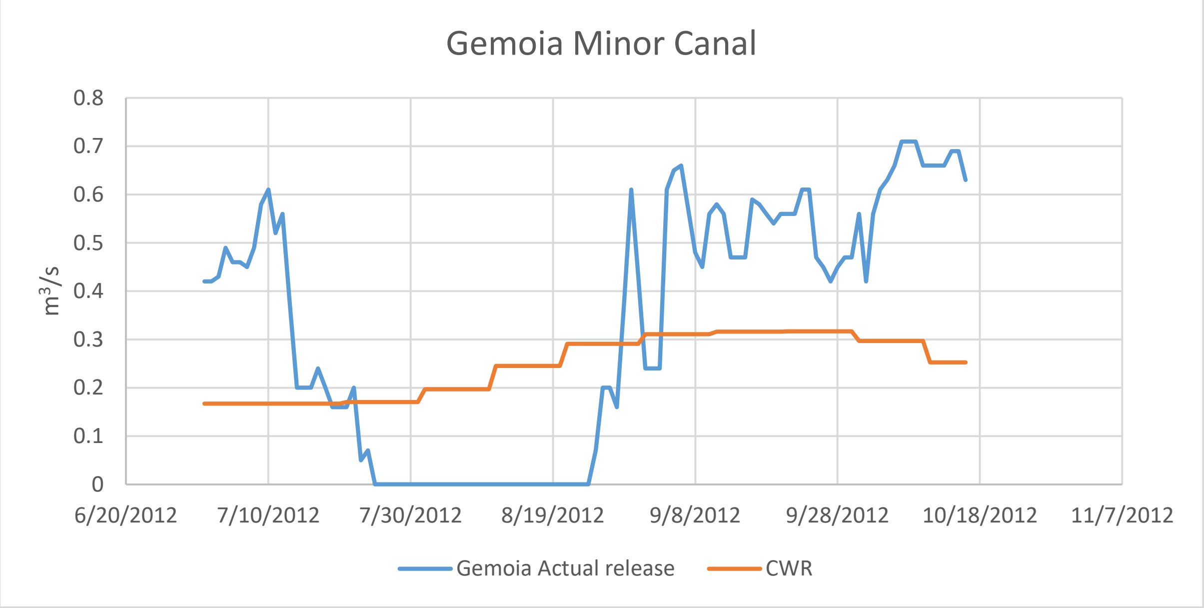


Figure 20. Gemoia actual Release versus actual crop water requirement

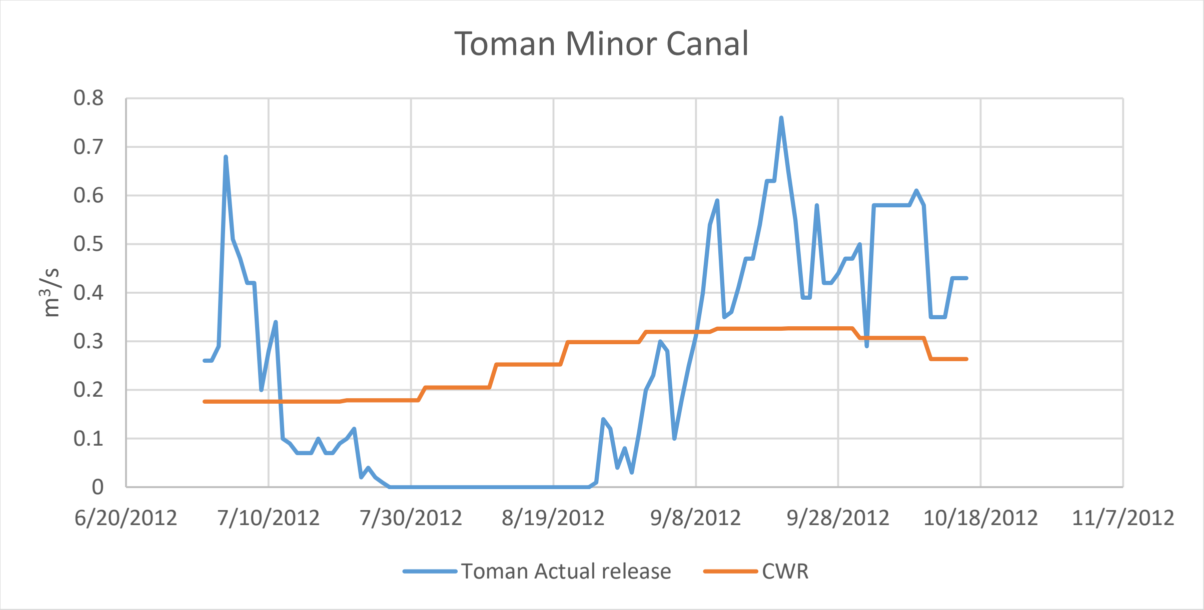


Figure 21. Toman actual Release versus actual crop water requirement

As stated before, the core of the MASSCOTE analysis is the canals operation, as they reflect clearly how the management is carried through. From the above water budget analysis, there are two main observations. The first is the fluctuation in water releases, the rise and fall occur rapidly within short periods, while the demand does not change in the same way. The second observation is that minor canals located on the upper reach of the major canals tend to have less water released, to some extent, than the actual CWR in the period after the rainy season – as for example is visible for minor canals of G/Elhoush and Ballola. Minors located in the downstream reach of Zananda major canals, however, generally recorded higher released discharges than the actual CWR – as for example can be seen Gemoia and Toman minor canals. This is an interesting observation, as it goes against the pattern one expects in gravity irrigation systems in terms of upstream and downstream water availability.

The uncertainties associated with the systems operation make it hard to find a reasonable explanation for such fluctuations and differences. Yet, it is considered to stand as a good starting point for the next chapter of modeling the operation strategies in Zananda major canal and Toman minor canal.

3.3 Outcomes and what to Model

From the previous two Gezira’s, we can notice there is a huge variation between the current state and the original or modified design state as appearing in the official documents. This is seen clearly in all components of the scheme.

1. There are differences in terms of farming and intensification in crops being grown. Also, farmers have more choice to determine which crops to grow.
2. This is reflected in the crop water requirements, water demands, hence water delivery to satisfy these demands.
3. The time of irrigation changed drastically from fixed duration of seven days and irrigation interval of 14 days to a continuous irrigation status.
4. In terms of the canal system, the main change is noticed in the minor canals level, where the operation has changed from the night storage system into the continuous system with no supervision from the responsible staff.
5. On the operation and maintenance side, due to limited budgets, maintenance works are only carried out for critical situations. Maintenance is not, however, done according to proper bathymetric surveys.
6. It is assumed that the removal of silts will lead to obtaining the initial design of the canal, but sometimes over-digging occurs and the cross-section is deepened or widened as shown in figure 10 in section 3.2.

The unsupervised operation of the minor canals may lead to unpredicted fluctuations in the canal water flows as seen for the minors, but this is not clear, given the many points of influence that the water needs to cross in the Gezira canal system. In terms of decisions, the operation of minors canals and field courses is supposed to follow a predefined scheduling as shown in appendix, yet this current situation of operation is mainly dependent on the judgment of the farmers. As several farmers lack awareness and knowledge of irrigation water application, they irrigate using the concept that more water standing in the field is better for the crops. This contradicts the crop water requirements, and over-timing of irrigation regularly leads to waterlogging.

As stated in the scope of the study, this research is intended to handle the issue of operation and water delivery. Taking the water requirement component, we study how these can be delivered to the fields. We want to model the three types of water demand approaches: the duty system, the actual crop water requirement system using Farbrother factors, and the remote sensing approach. The first two approaches are carried through the indenting system as explained earlier, hence the amount of water released is known a week before the actual period of time that the water is used. When using remote sensing approaches, this period changes to real time (possibly in terms of days). The remote sensing methods could also reduce the effort on the field and block inspectors. When using satellite imagery, less ground efforts are needed, although perhaps ground observations are needed as confirmation of these satellite estimates.

We want to use hydraulic modeling to see how the canal system behaves under the first two systems and the remote sensing approach, as it remains to be seen whether the canal system can deliver the water requirements fast enough. Therefore, we want to determine up to what period of time the system can deliver the required water demands (obtained by remote sensing). This also determines the period of prediction for the remote sensing methods, whether it should be one day, two days, and so. Of course, the more days of prediction, the less the accuracy of the remotely senses water needs becomes. In the modeling section below, the main focus will be on the canalization system, and its response in terms of how much time is required to deliver water if remote sensing methods are used in the irrigation scheme.

The modelling is carried for the Zananda major canal and the Toman minor canal, given their availability of the required data for modelling from a previous study carried by Osman in 2015.

4. Modelling Design

In this chapter, we will model the different operation strategies that were used in the past (Water duty System) and the ones currently being used (Actual CWR). Further, we will test the system's response to the new imposed strategies (Remote Sensing). Following the same steps from the previous chapter, we first need to know the canalization system we are dealing with, before introducing new measures. In the first part of the modeling, we tested the systems under the 'old' operation strategies. We have separated the system into the major canal serving all the canals, and then we took one minor canal, Toman minor canal, to represent the rest of minor canals. On the second part of the modeling, we combined the major and minor canal and applied our three scenarios, to see how the overall system that is modelled will respond. The modelling remains a first indication of which issues are to be expected, as its scope has remained limited.

It is important to mention that due to corona circumstances, it was not feasible to travel to Sudan for measurements, yet, the data used for modelling was obtained from the Civil Engineering Department, University of Khartoum, and the Hydraulics Research Center, Ministry of Irrigation and Water Resources – Sudan. This data includes, not limited to, canals cross-sections, cropped areas, canals longitudinal profiles, and weir settings. The data was obtained for the summer season of the year 2012.

4.1. Study Area

The location of the study area within the Gezira Scheme is shown in Figure 22. The Zananda Major Canal was selected for modeling major canal operation. It is located within the upstream part of the Gezira canalization system. It has a total length of 17 km. The canal delivers water to 9 minor canals with a total command area of about 8520 ha. Two cross regulators, movable weirs (MW-II), were installed at 9.1 and 12.5 km from the offtake with a crest width of 2 m and 1.3 m respectively. Table 7 illustrates the design characteristics of Zananda major canal.

On the minor canal level, Toman Minor canal was chosen to be modelled. It takes water from Zananda major canal at chainage 12.5 km, by means of MW-I. It has a total length of 6 km.
It serves a command area of about 772 ha. The area is divided into 21 Nimras. Each Nimra is irrigated by an Abu Ishreen canal as shown in Figure 24. The canal has four reaches divided by two night storage weirs (NS) and a pipe regulator (diameter 0.76 m) at the head of the fourth reach. Tables 8 gives information about the design characteristics of Toman minor canal.

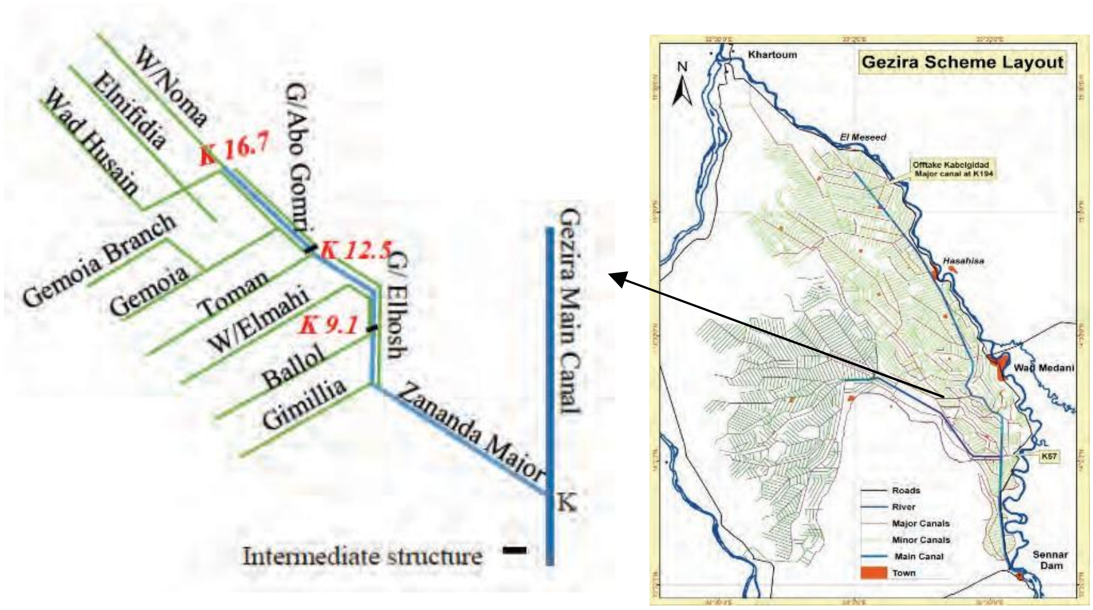


Figure 22. Study area of Gezira scheme (Osman,2015)

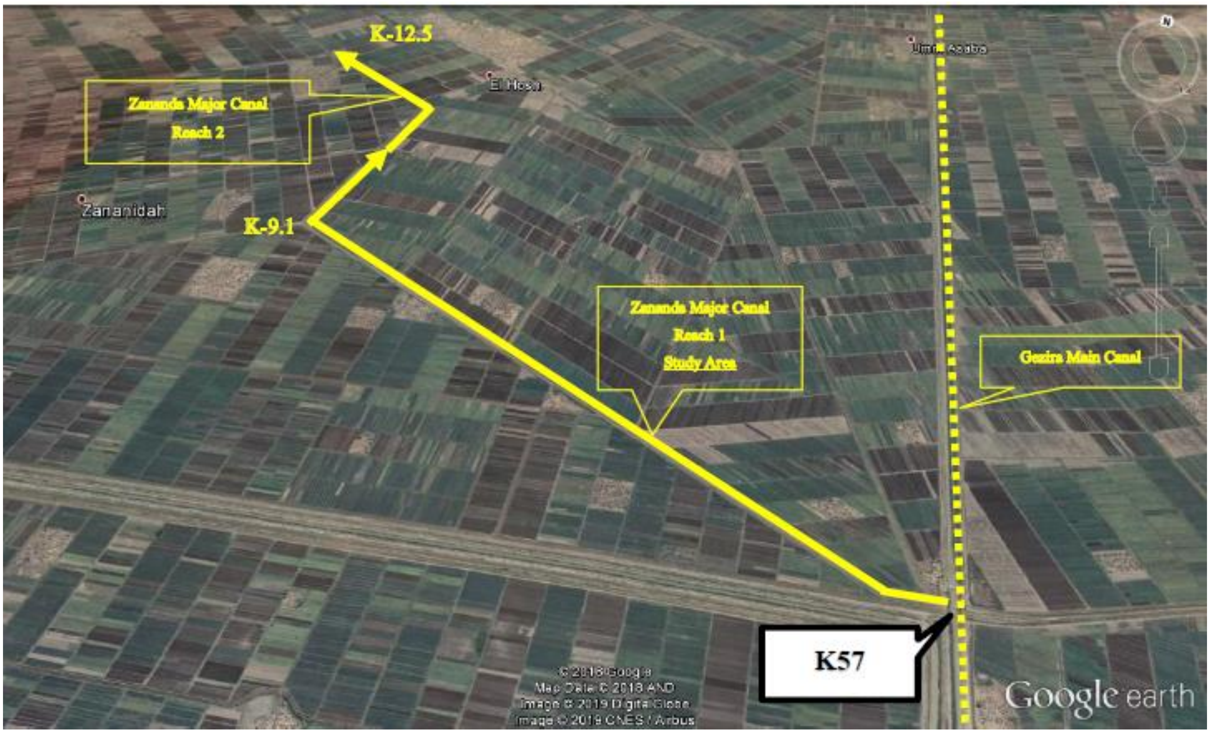


Figure 23. Google earth map of Zananda major canal (Osman,2015)

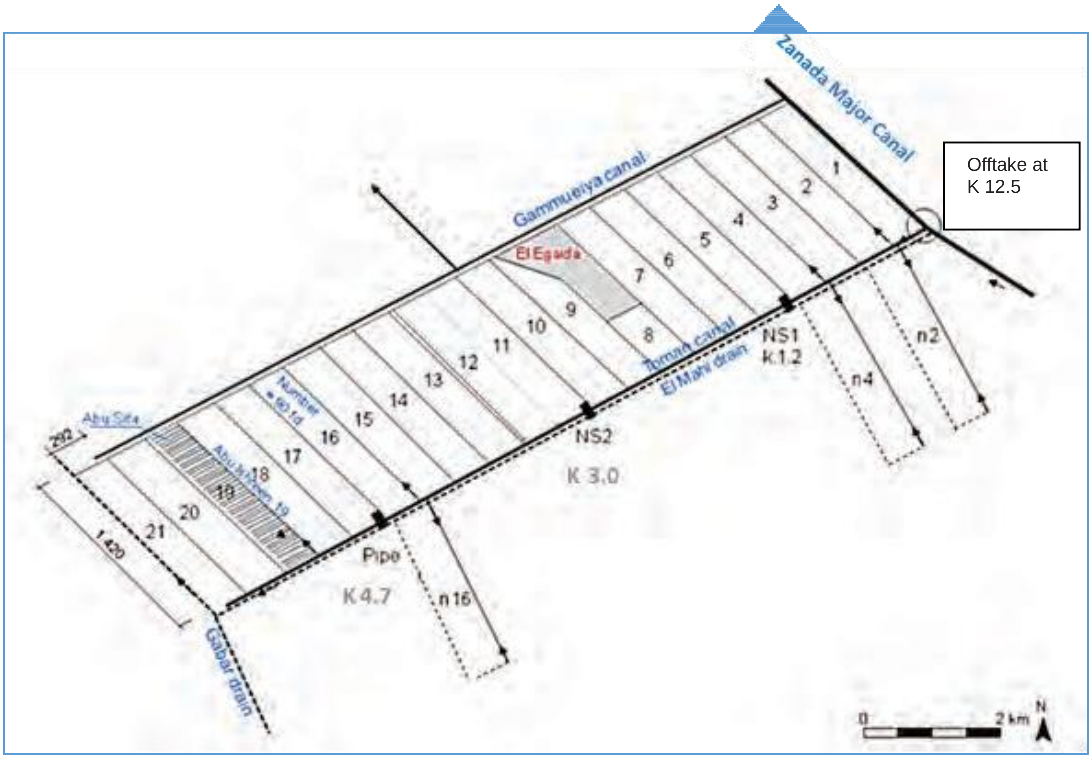


Figure 24. Irrigated area of Toman Minor Canal (Aalbers, 2012).

Table 7. Design Characteristics of Zananda Major Canal (MoIWR)

Canal characteristic	Value
Position of offtake along the main canal (km)	57
Command area (ha)	8,520
Effective length (km)	17
Number of reaches	3
Supplied minor canals	9
Design discharge (m^3/s)	3.52
Full capacity of the canal (m^3/s)	5.5

Table 8. Design Characteristics of Toman Minor Canal (MoIWR)

Canal characteristic	Value
Position of offtake along the major canal (km)	12.5
Command area (ha)	772
Effective length (km)	4.6
Number of reaches	4
Design discharge (m^3/s)	0.46
Head regulator: weir width (m)	0.8
Night-storage weirs	2

Table 9. Different types of structures along the canals under study (MoIWR)

Canal	Distance from offtake (km)	Location	Type of structure	Width (m)
Zananda	0	Offtake of Zananda at 57 km from Sennar Dam	Tow sluice gates	2
	7.4	Gimeliya offtake	MW-I	0.8
	7.4	G/ Hosh offtake	MW-I	0.8
	9.1	Cross structure-1	MW-II	2
	9.1	Ballola offtake	MW-I	0.8
	9.1	W/ Elmahi offtake	MW-II	1
	12.5	Cross structure-2	MW-II	1.3
	12.5	G/ Abu Gimri offtake	MW-I	0.35
	12.5	Gommuiya offtake	MW-I	1
	12.5	Toman offtake	MW-I	0.8
Toman	1.2 km from Toman offtake	Cross structure	NS-1	Diameter 0.91
	3 km from Toman offtake	Cross structure	NS-2	Diameter 0.91
	4.7 km from Toman offtake	Cross structure	PR	Diameter 0.67

4.2. Input data:

4.2.1. Water Demands:

Crop Water Requirements:

As mentioned earlier in the MASSCOTE chapter, there are two methods that have been used in the scheme for determining the water demands (CWR): the empirical method, which estimates the requirements of all crops at 30 m^3/feddan/day inclusive of field losses, and the actual CWR method generated by Farbrother (1974). In the empirical method, all crops are estimated to have the same water requirement. This method has been used until the late 1960s, after which studies were carried by Farbrother in order to determine the values of the crop factors, hence the crop water requirement depending on the Penman method. Values of CWR were determined for all main crops under the local climatic and soil conditions of the scheme; these values are calculated at the field outlet pipe level. The Farbrother method defined the crop water requirement as the amount of water that is equal to the maximum crop water use (CWU). The crop factors (K_f) were determined as the ratio between the CWU and the Penman evaporation (E_o). Therefore, the CWR is estimated by multiplying the k_f of the crop during the specified period with the relevant E_o obtained from the Gezira Meteorological Center. More details about the equation and crop factors is provided in appendix B.

For the modelling, actual crop water requirements were computed for the summer season of 2012, based on the results of Farbrother's study. These are presented in Table 10. Adam (2005) stated that the recent studies confirmed that Farbrother's factors are still valid and can continue to be applied in Gezira.

Effective rainfall:

In the area of Gezira, the rainfall shows an average of 300mm during the summer season (Ahmed, 2009). There are multiple methods to assess the contribution of rainwater supply for irrigation, such as the moisture available index (MAI) and ratio of moisture availability (RMA). The RMA is the ration of actual rainfall to the ET_c. This study will take the effective rainfall (P_e) into consideration, as it is easier to apply and fieldwork was not possible. The effective rainfall is estimated to be about 80% of actual rainfall (Osman, 2015). Table 1 in chapter 2, presents the rainfall records of 2012 from the Meteorological Corporation Records, Wad Madani.

Evaporation:

The losses in the canals are mainly due to evaporation. Due to the impermeable clay soil, there are no losses due to percolation neither canal seepage. The average monthly evaporation in July, August, September and October is 244, 206, 206 and 204 mm respectively (Adam, 2005). The evaporation in the Zananda system has been computed. The lengths of the major canal and all minor canals, supplied by the major canal, are about 17 and 6 km respectively. When the canals were supplied at their full capacity, the surface width was about 15 and 8.4 m for the major and minor canals respectively. It was found that the evaporation losses in the Zananda system was about 0.02 Mm^3 during the summer season (4 months). However, the evaporation losses were rather small and represented about 0.03% of the supply, when the canals were operated with their full capacity (the release is 58.4 Mm^3) during that period. The calculation is carried with the full capacity discharge of 5.5 m^3/s, while in practice the discharge is much less. As evaporation from the canals will remain very low, it has been neglected in the computation of the modelling scenarios.

Table 10. Crop water requirement in m3/ha/day (Farbrother, 1974)

Month	Period	Cotton	Groundnuts	Sorghum	Vegetables
July	1-10		42.4	190.5	63.3
	11-20		41.9	39.5	63.3
	21-31		43.1	40.2	58.6
August	1-10	71.4	46.2	47.6	54.5
	11-20	32.4	50.7	61.2	51.9
	21-31	32.9	60.0	72.6	52.9
September	1-10	38.8	68.8	76.2	54.5
	11-20	46.2	75.2	76.0	55.2
	21-30	58.6	75.9	76.0	55.2
October	1-10	67.4	72.9	70.7	54.5
	11-20	73.8	67.9	58.6	52.9
	21-31	76.9	56.9	41.7	51.2
Sowing date		1 - 10 Aug	21 - 30 Jun	1 - 10 Jul	

The major crops in the study area are groundnut, sorghum, cotton, vegetables and wheat (which is cultivated in winter). Based on the law of 2005, farmers have the right to choose their crops. The Sudan Cotton Company finances the farmers who grow cotton by supplying fertilizers and pesticides. It is also responsible for the land preparation and selling cotton. The income of the crop is shared between the company and the farmers. Due to the company policies with respect to payment (delay in payment), the farmers prefer to grow sorghum instead of cotton, which is also less costly. Thus, cotton is not cultivated anymore in most of the command area. Figure 25 displays the cropping pattern in 2012, in the area supplied by Zananda Major Canal as recorded by the SGB.

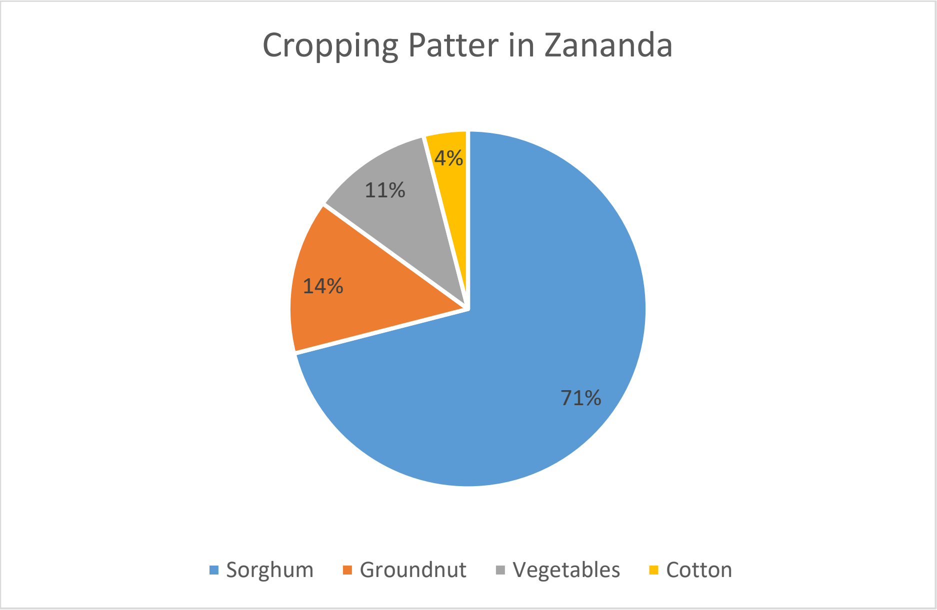


Figure 25. Cropping pattern in the area supplied by Zananda Major Canal

Table 11 below illustrates the cultivated area for each crop for all the minor canals being supplied by Zananda major canal. Due to heavy rainfall during the flood season of 2012, the amount of water supply to the scheme was reduced during the rainy season. This is confirmed by the water budget graphs we saw earlier in the MASSCOTE chapter.

Table 11. Total cropped area in 2012 in Zananda Major Canal system (MoIWR)

Canals	**Cotton (ha)**	**Sorghum (ha)**	**Groundnut (ha)**	**Garden (ha)**	**Total area (ha)**
Gimillia	0	256	139	0	395
G/ Elhosh	0	241	123	17	381
Ballola	0	407	92	10	508
W/ Elmahi	0	512	47	14	575
G/ Abu Gomri	0	120	29	8	158
Toman	0	271	95	8	374
Gemoia Branch	0	281	79	0	360

For the minor canal level, Figure 26 shows the cropping pattern of 2012 in the area supplied by Toman Minor Canal. Sorghum represents the largest cultivated area.

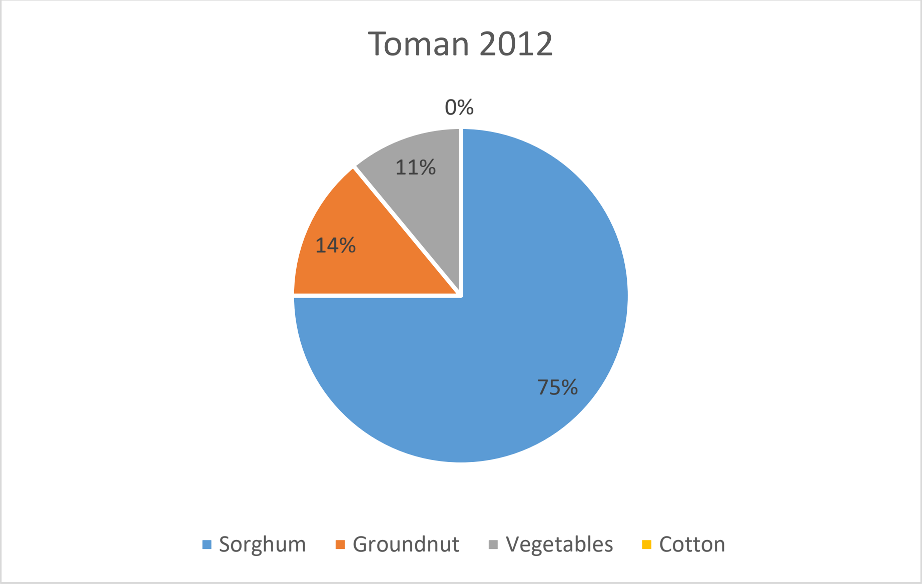


Figure 26. Cropping pattern in the area supplied by Toman Minor Canal

4.2.2. Cross-Sections

For the Zananda major canal, the design cross-section of the canal has been used in the model for the base scenarios, as this allows for evaluating basic model performance. For the current scenarios, two cross sections are available, one from chainage 4200 and the second from chainage 8400. Figure 27 shows the variation in the cross sections between the design and the current situation of the canal. The reasons for this variation are the improper desilting campaigns or clearance activities, in addition to sedimentation. For Toman canal, figure 28 shows the design and current cross sections.

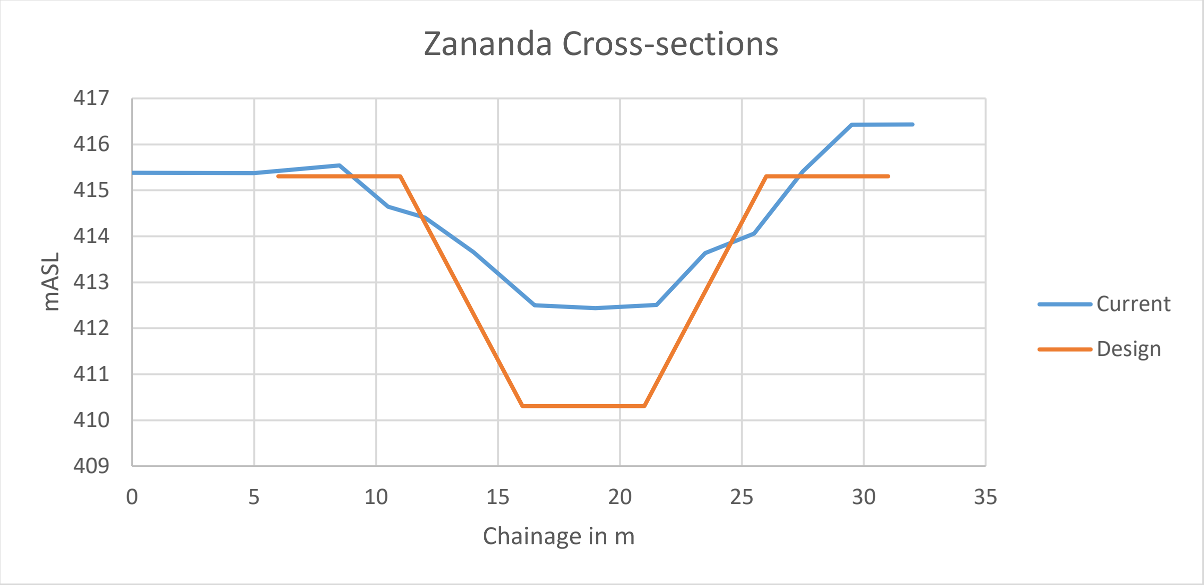


Figure 27.Cross-section of Zananda major canal at chainage 4200 m from offtake.

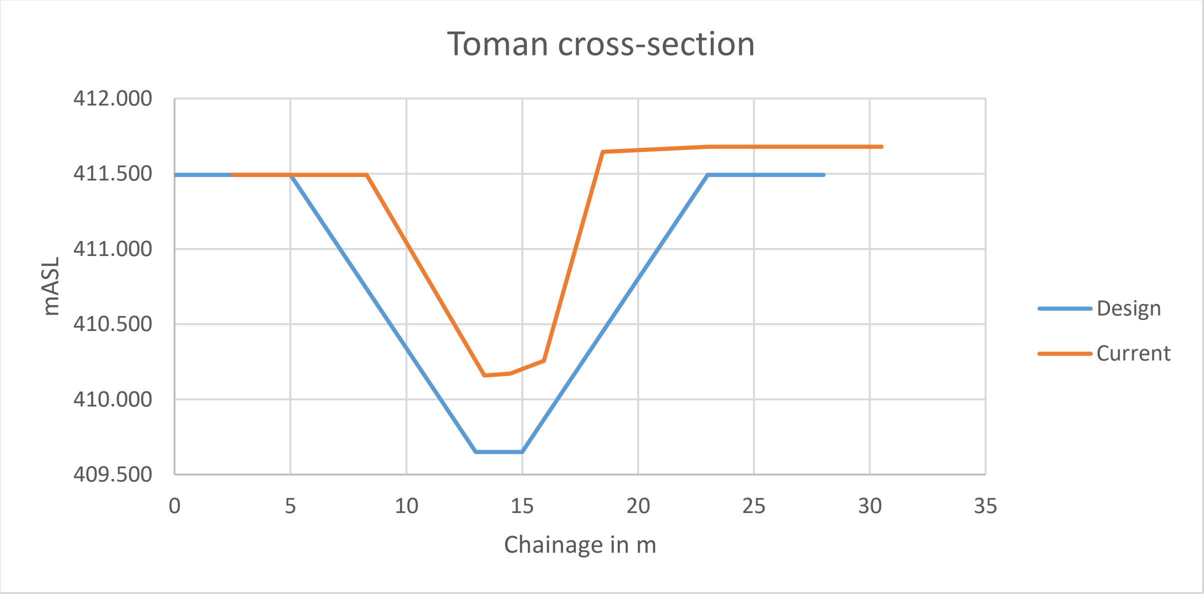


Figure 28. Toman Cross-section at chainage 0.00 from Offtake

4.2.3. Slope

Following the same scope as for the cross-sections, two data sets were used in modelling the slope of Zananda major canal and Toman minor canal. Figure 29 reflects clearly the effect of sedimentation on the bed level, and the over-digging in the second reach of the canal. An average of 1.53 m addition in bed level is present in the first reach (9100 m), while an over-digging of 0.4 m is present in some parts of the second reach (9100m -12500m) – even though the level is still higher than designed. We assumed that the sedimentation loading was uniform throughout the whole reach.

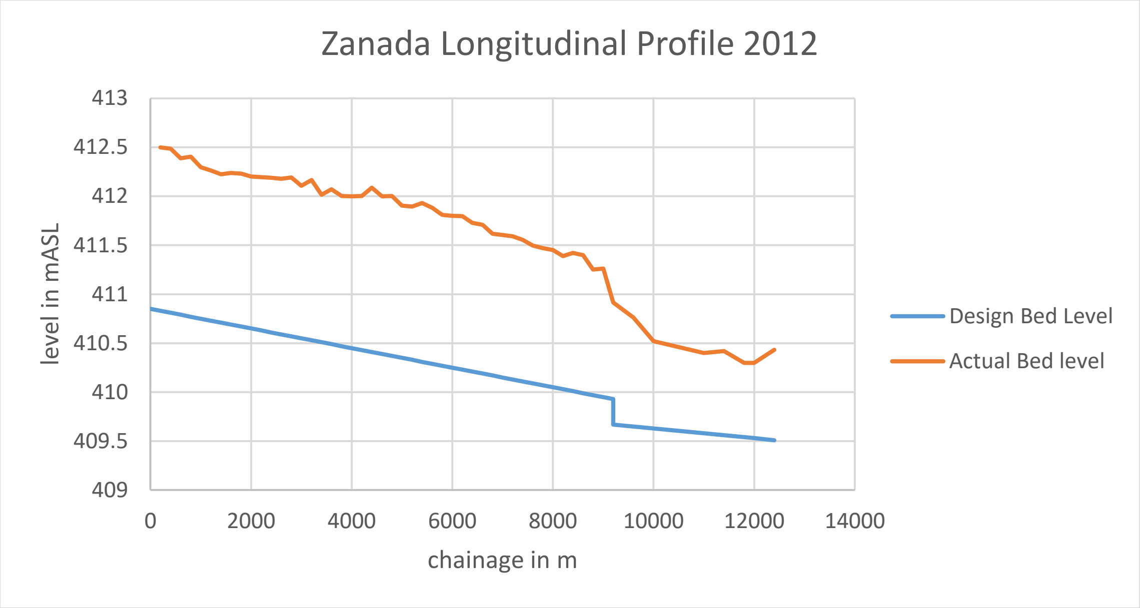


Figure 29. Design versus actual slope of Zananda Canal

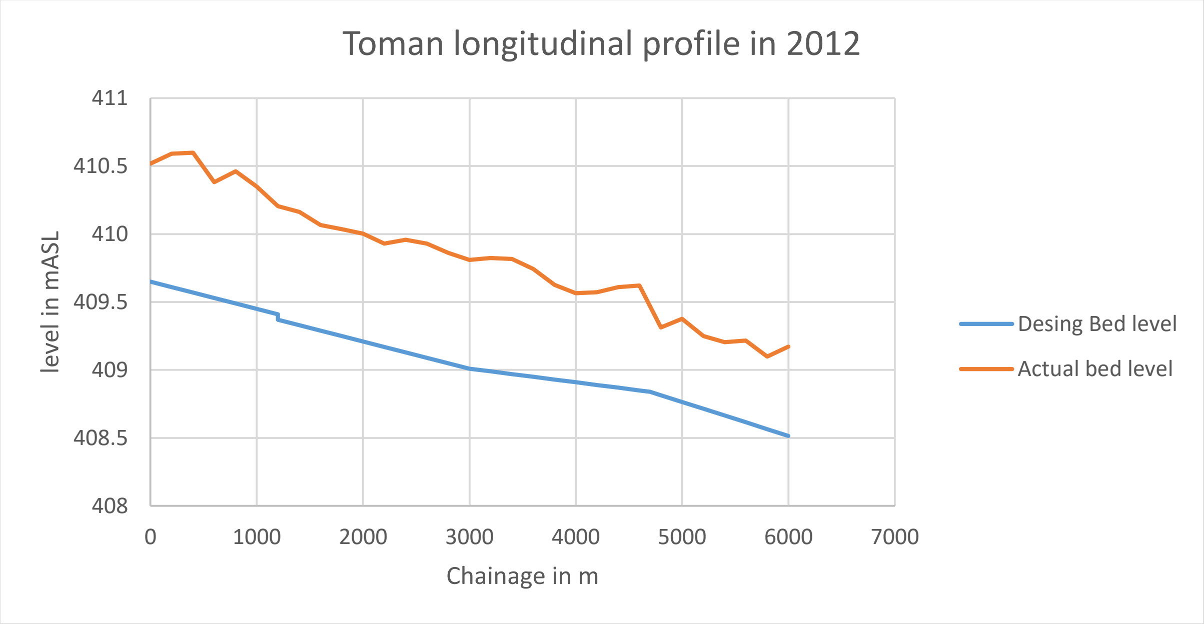


Figure 30. Design versus actual slope of Toman minor Canal

4.3. Software Program:

The SOBEK software package (version 3.7.21) has been used to model the Zananda major canal and Toman minor canal as part of the water distribution system in the Gezira scheme. The use of computer models increases the understanding of the dynamics in the water distribution system for different operation scenarios. The software has several applications, such as irrigation and drainage, open channel hydraulics, river systems, sewerage and urban drainage systems, water quality predictions and many others. It has been developed by Deltares. In this research, the 1DFlow model has been used (Deltares, 2020).

The model works with the complete de Saint Venant (1871) Equations for unsteady flow, including transient flow phenomena and backwater profiles. These equations are based upon the following assumptions:

- The flow is one-dimensional i.e. the velocity can be represented by a uniform flow over the cross-section and the water level can be assumed to be horizontal across the section.
- The streamline curvature is small and the vertical accelerations are negligible, hence the pressure is hydrostatic.
- The effects of boundary friction and turbulence can be accounted for through resistance laws analogous to those used for steady flow.
- The average channel bed slope is small so that the cosine of the angle it makes with the horizontal may be replace by unity.

For the one dimensional flow, the following equations are solved:

Continuity equation 1D;

$$\boldsymbol{\frac{\partial A_T}{\partial t} + \frac{\partial Q}{\partial x} = q_{lat}}$$

Where:

A_T	Total area (sum of flow area and storage area) (m^2)
Q	Discharge (m^3/s)
q_{lat}	Lateral discharge per unit length (m^2/s). Positive value refers to inflow. Negative value refers to outflow.

Momentum equation 1D;

$$\boldsymbol{\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A_F}\right) + gA_F\frac{\partial \zeta}{\partial x} + \frac{gQ|Q|}{C^2RA_F} - w_f\frac{T_{wind}}{P_w} + gA_F\frac{\xi Q|Q|}{L_x} = 0}$$

Where:

A_F	Flow area (m^2)
C	Chézy value (m$^{1/2}$/s)
G	Acceleration due to gravity (m/s^2)
ζ	Water level (m)
L_x	Length of branch segment accommodating an Extra Resistance Node (m)
Q	Discharge (m^3/s)
R	Hydraulic radius (m)
t	Time (s)
w_f	Water surface width (m)
X	Distance along the channel axis (m)
P_w	Density of fresh water (kg/m^3)

T_{wind} Wind shear stress (N/m^2)
ξ Extra Resistance coefficient(s^2/m^5)

Initial Conditions:

The initial conditions are the water levels or depths and the discharges at the beginning of the simulation. The initial conditions are defined over a branch (water level and depth at the ζ -calculation points, discharges at the branch segments). Therefore, the water level that initially should be taken at connection nodes is not strictly defined. This happens when, for example, branch 1 with initial water level 0.5 is connected by a node to branch 2 with initial water level 0.6. In that case the water level at the connection node is set to the lowest value of the connected branches (0.5). Because the ζ -calculation point at the end of branch 1, the connection node and the ζ -calculation point at the beginning of branch 2 have the same location, the water levels of these three points are set to 0.5 (Deltares, 2020).

Boundary Conditions:

The boundary conditions can be applied at the locations where the model network ends with a boundary node. In order to solve the water flow equations (continuity equation and momentum equation), information about the water flow at the model boundaries must be supplied.

At each boundary node, one condition for the water flow must be specified. The following options are available:

- Discharge (constant, tabulated function of time, tabulated function of the water level).
- Water level (constant, tabulated function of time).

The upstream boundary condition is the inflow discharge into Zananda, given in daily time series. The downstream boundary condition is the water level at the end of the canal.

Model Setup

The model was setup according to two phases. First, the major and minor canals were modelled separately. For the major canal, it was modelled using two situations: the initial design characteristics and the current situation of the canal. Then, the inflow coming from the major canals was inserted as boundary inflow for the minor canal. The purpose of this phase is to test the previous operation strategies and how the system was operated in the past. Then, these two models were combined in one model to represent the whole system under the current situation. In this phase, we want to test the proposed new CWR strategies.

The base models depend on the initial design of the canals system, and the water demand approach used in early times. The current model reflects the actual status of the system in 2012, and the actual water released and crop water requirements. The locations of minor canals offtakes are described in table 9. The width and the side slope of each reach were defined in the model. The inflow discharge is set in time series at the upstream boundary. The outflow (lateral outflow) along the canal during the simulation period was also set in time series. The types of structures and their properties such as the discharge coefficient, width of weirs were defined in the model.

4.4. Scenarios

For the first part of modelling (Separate Zananda and Toman), Figure 31 gives an overall description on the scenarios development. The scenarios were generated in a way to investigate the response of the water distribution under various water demands methods, which are the duty system and the actual crop water requirements. These water demands methods were tested first on the based model of the system's characteristics (as initially designed) and then on the current situation of the system. As explained in chapter 3, the water distribution system of the Gezira scheme established the minor canals to act as night storage systems, with majors acting as conveyance systems. In recent years, all the canals are operated under continuous flow condition. These two scenarios were tested on the Toman minor canal using the actual crop water requirement and the current cross-sections of the canal.

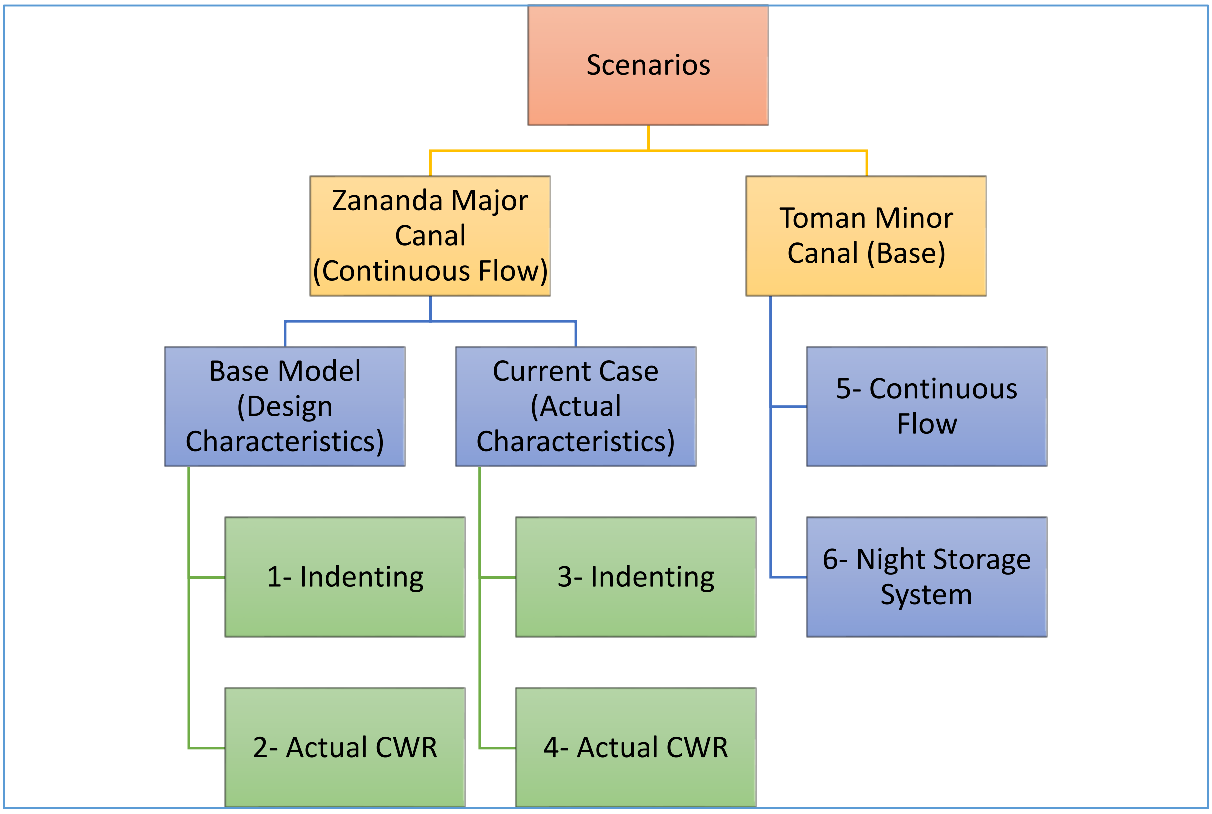


Figure 31. This hierarchy illustrates the various scenarios to be tested

For the second part (Combined model), the scenarios were generated in a way to investigate how the system would respond under different demands that vary in location (U/S, middle, and D/S) along the major canal – to represent the possible need of the canal system to respond to quickly changing water demands being derived from remotely sensed water needs. Four scenarios were developed. For the first three scenarios, three minor canals were taken, depending on their location (U/S, middle, and D/S), in order to see how the demand at each different minor location will affect the overall system. For the fourth scenario, we assumed that minors will demand water all together at the same time, hence increasing the magnitude of water demand in the system. All these scenarios are carried out using the current characteristics of the canalization system. Figure 32 shows the scenarios for the combined system.

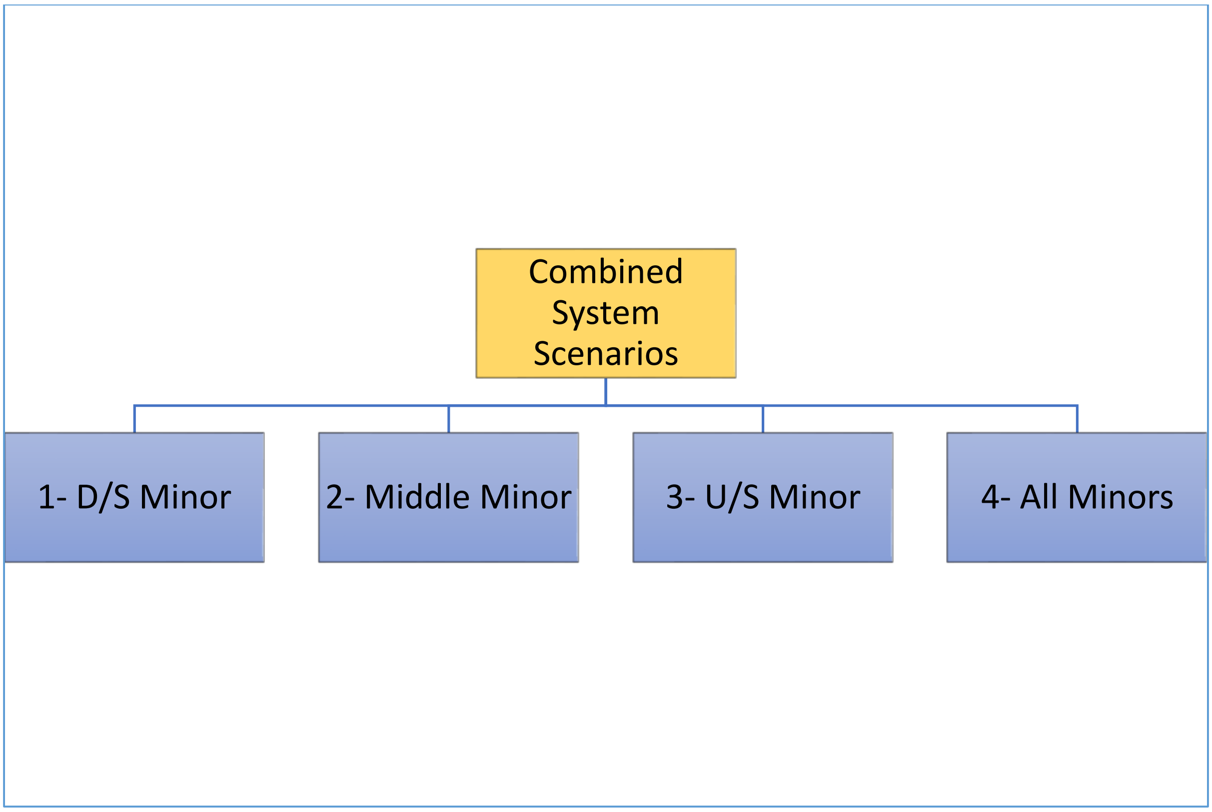


Figure 32. Scenarios representing abstractions from various location of minor canals setups

4.5 Zananda Major Canal

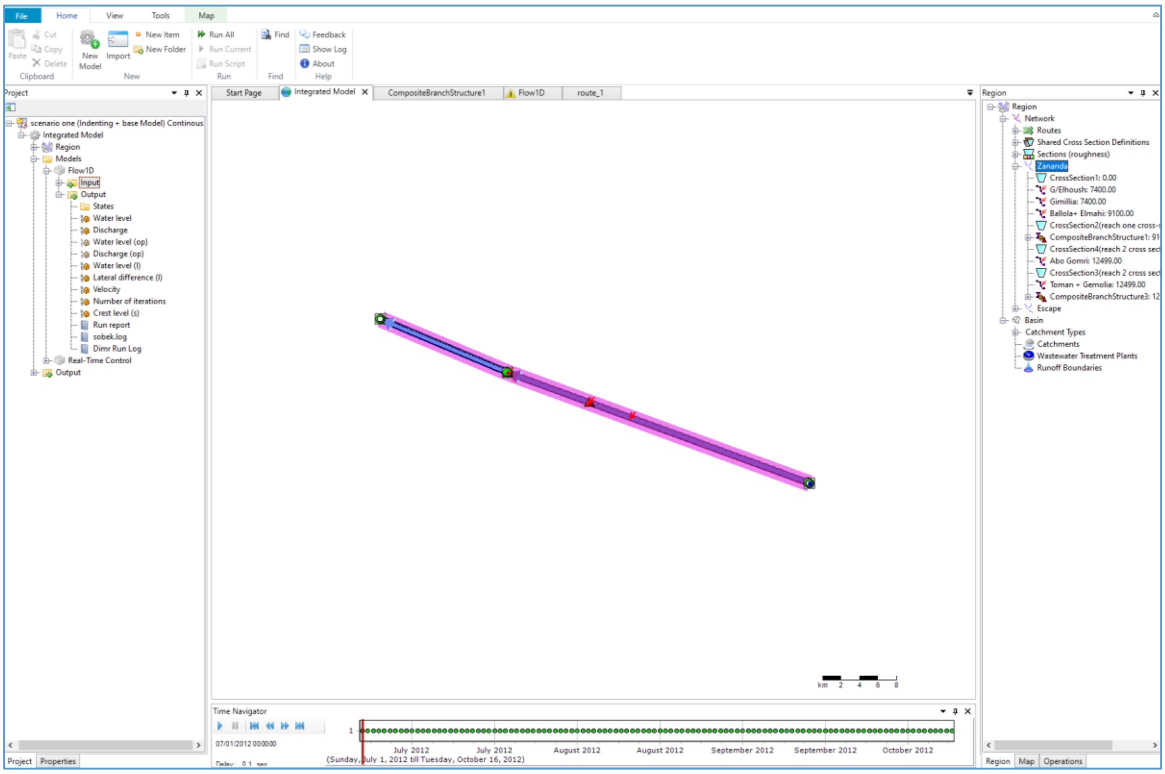


Figure 33. shows the SOBEK interface (Zananda as an example)

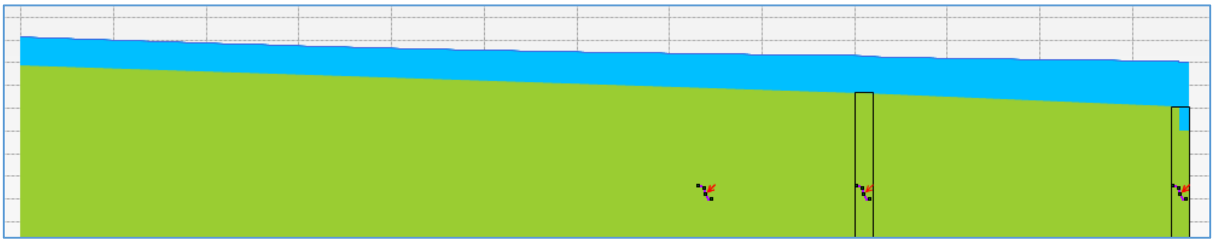


Figure 34. The longitudinal profile of Zananda major canal with back water curve

Scenario 1: Operation based on the duty system (Base Model)

The simulation for Scenario 1 was performed to investigate the system's behavior, when the canal is operated based on the duty system. The water duty is a procedure for water allocation that was adopted in Gezira Scheme as was elaborated earlier. Although this system (duty) was absent during the last years, it can give an approximate estimation of the water requirement over a season. The duty for the study area was estimated at 71.4 m^3/ha/day (30 m^3/feddan/day) for all crops, including losses at the head of the Abu Ishreen canal (Plusquellec, 1990). The sowing date for cotton was between 1 and 10 August, for groundnut it was between 20 and 30 July and for sorghum between 1 and 10 June (MoIWR). Therefore, the indent during July was based on the cropped area with sorghum (excluding the first irrigation), groundnut and garden. From 1 August, cotton is added to the cropping pattern. In 2012, cotton was not grown in the Zananda Major, hence the duty is the same throughout the whole summer season. For the Zananda major canal setup, the inflow was set as the design discharge (3.52 m^3/sec). The bed slopes were set 0.00013 and 0.00018 for the first and second reach respectively. The average bed width is 5 m for the first reach and 4 m for the second reach. The average side slope was (1:1.1) for the first reach and (1:1) for second reach (MoIWR). The canal roughness has been represented by manning coefficient with value of 0.03 m/sec^2. Gismalla and Fadul (2011) concluded that the roughness coefficient in the Gezira scheme ranges between 0.022 – 0.033 m/sec^2. The crest levels of the weirs were set to the average levels.

Table 12. Application of duty water for minors served by Zananda Major canal

Canals	**July – October**	
	Area (ha)	**Indent (m3/s)**
Gimeliya	395	0.33
G/ Hosh	381	0.31
Ballola	508	0.42
W/ Elmahi	575	0.48
G/ Abu Gimri	158	0.13
Toman	374	0.31
Gommuiya Br	360	0.30

Results will be shown in 5 locations to represent the system as shown in figure 35 below. They are shown in ascending order from the upstream to downstream. They are; 1. D/S of the major offtake, 2. middle of the first reach, 3. U/S of the first lateral outflow, 4. U/S of the first weir and second lateral outflow, and 5. U/S of the second weir and third lateral outflow.

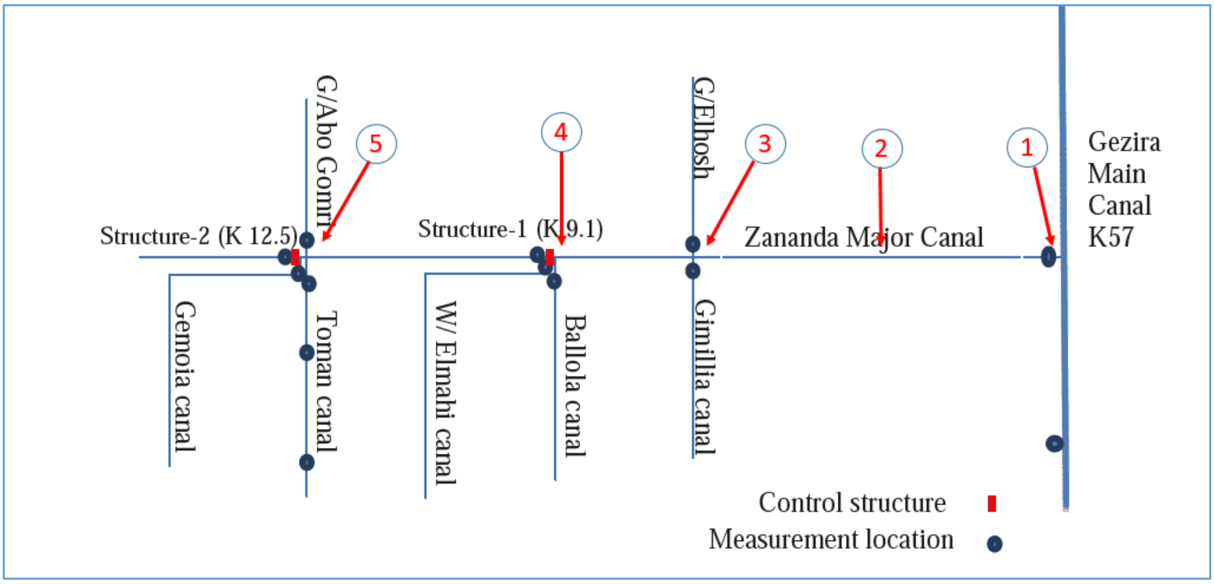


Figure 35. Location of representation results

In figure 36 below, we can see that the water levels are stable and almost constant in all locations throughout the whole summer season in this first scenario. This is clearly related to the constant design inflow of the Zananda major canal and the constant duty system of the crop water requirements (Constant areas), with the weirs set at average.

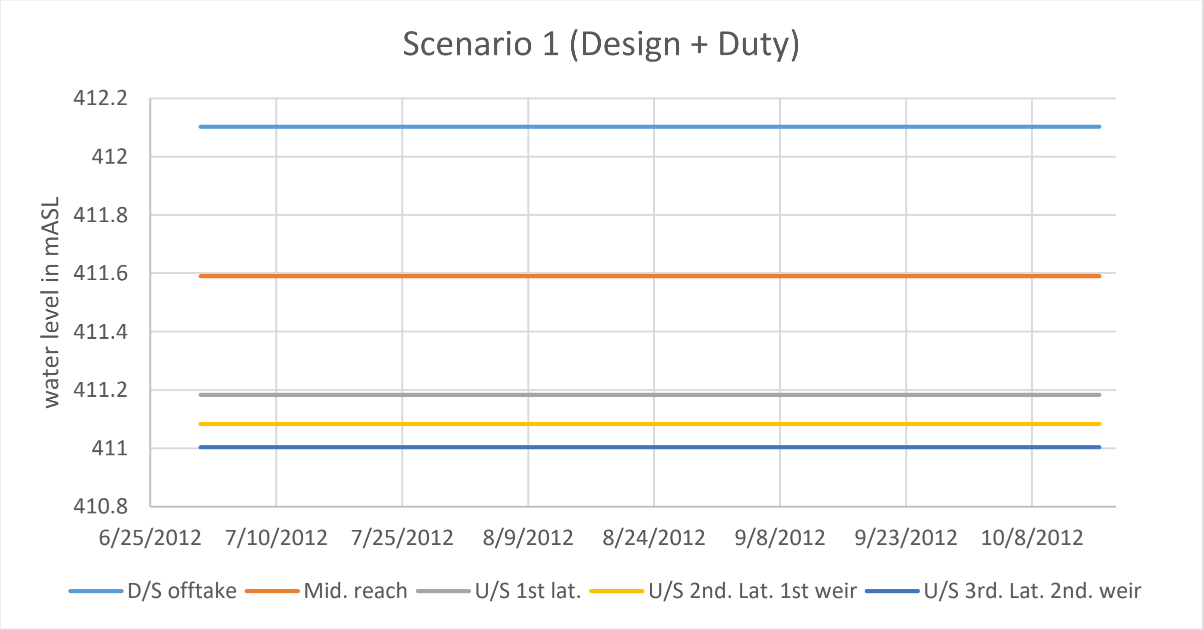


Figure 36. Scenario 1 water levels

Figure 37 below, shows the water depth for the same locations. They are, obviously, also constant throughout the season. We find downstream locations with larger water depths than upstream locations.

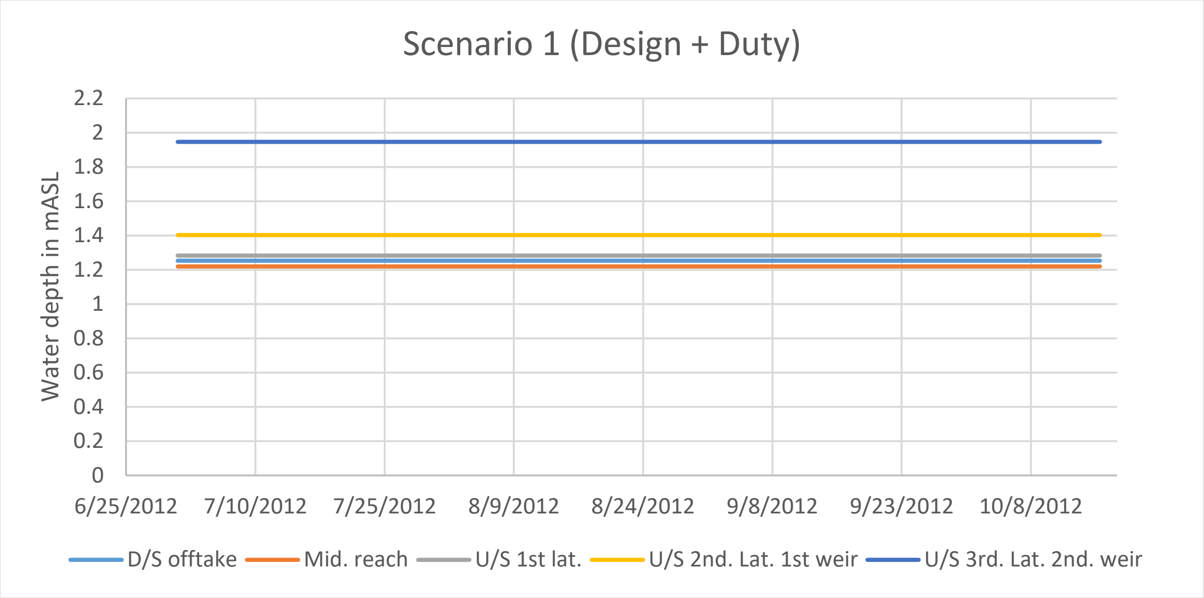


Figure 37. Scenario 1 water depths

Scenario 2: Operation based on the Actual CWR (Base Model)

In this scenario, the model has been run using the actual crop water requirement method by Farbrother (1974) for calculating the water demand. Table 10 in section 4.2 illustrated the CWR for each crop in m3/ha/day on a 10-day basis. Table 11 in the same section shows the cropped area for each minor canal. From the two tables, the actual CWR was generated as shown below in table 13 below on a 10-day basis.

Table 13. Actual Crop Water requirement for all minors served by Zananda Major Canal

Month	**Period (days)**	**Gimillia (m^3/s)**	**G/ Elhosh (m^3/s)**	**Ballola (m^3/s)**	**W/ Elmahi (m^3/s)**	**G/ Abu Gomri (m^3/s)**	**Toman (m^3/s)**	**Gemoia (m^3/s)**
July	1-10	0.19	0.18	0.24	0.27	0.07	0.18	0.17
	11-20	0.18	0.18	0.24	0.27	0.07	0.18	0.17
	21-31	0.19	0.19	0.24	0.27	0.08	0.18	0.17
August	1-10	0.22	0.21	0.28	0.32	0.09	0.21	0.20
	11-20	0.26	0.25	0.35	0.40	0.11	0.25	0.25
	21-31	0.31	0.30	0.41	0.47	0.13	0.30	0.29
Septembe r	1-10	0.34	0.32	0.44	0.50	0.13	0.32	0.31
	11-20	0.35	0.33	0.44	0.50	0.14	0.33	0.32
	21-30	0.35	0.33	0.45	0.50	0.14	0.33	0.32
October	1-10	0.33	0.31	0.42	0.47	0.13	0.31	0.30
	11-20	0.28	0.27	0.35	0.39	0.11	0.26	0.25
	21-31	0.22	0.21	0.26	0.29	0.08	0.20	0.19

The graphs below in figure 38 and 39, show the water levels and water depths respectively of the described locations when the actual CWR are used as water demands. There is a slight change due to change in outflow from laterals (CWR). The D/S offtake has a slight level fluctuation since it is far from the first laterals outflows. The closer to the outflow lateral and weirs, the more change is observed in water levels and depths.

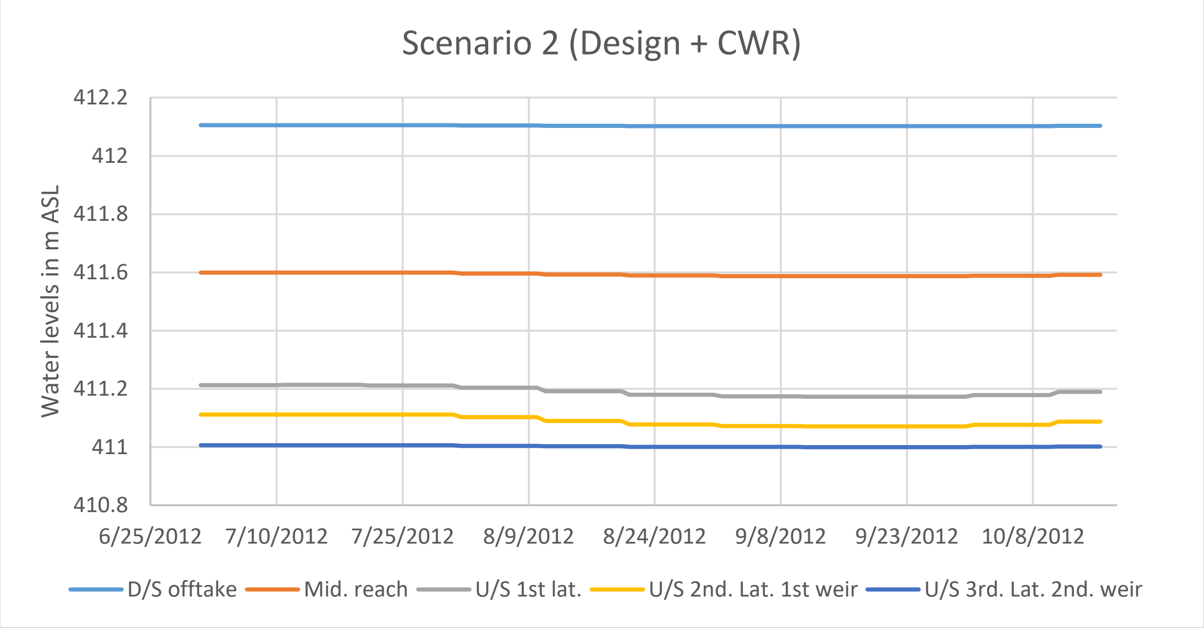


Figure 38. Scenario 2 water levels

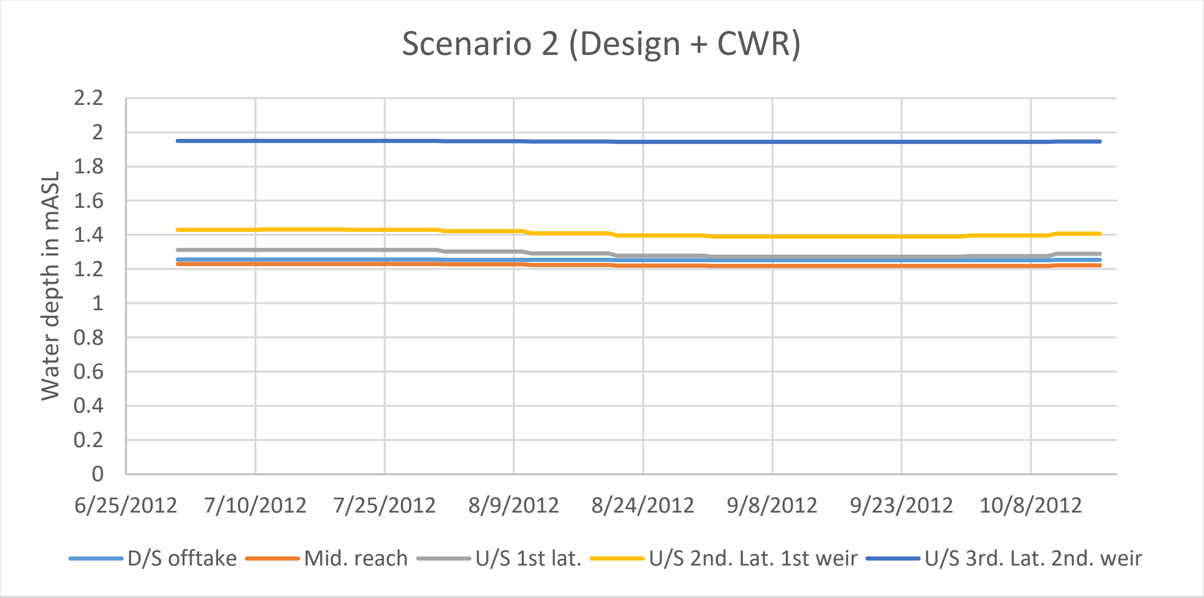


Figure 39. Scenario 2 water depths

Scenario 3: Operation based on the duty system under current situation

In this scenario, the system is modelled by taking the duty system as shown above, but under the current situation of the canal characteristics. The cross sections and bed level data of 2012 were used. The actual release of Zananda major canal is entered as the inflow discharge. Although this scenario is most likely not to occur, yet it gives more understanding of the systems response and behavior, if the duty system was still being applied. Table 18 in appendix C, illustrates the releases of Zananda major canal and minor canals and crest levels in the summer season of 2012.

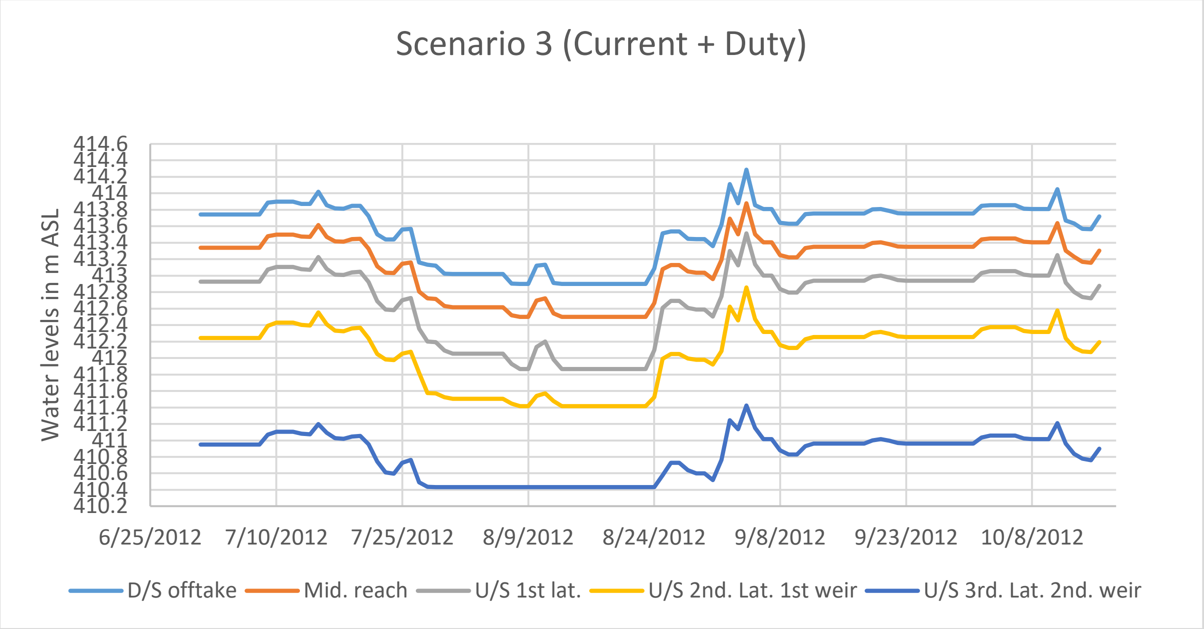


Figure 40. Scenario 3 water levels

From the above graph, we can notice that the fixed duty system does not create different patterns of the water level for the different locations. As can be seen, the downstream locations have the same trend of water level as the U/S offtake. Therefore, the changing inflow discharge is the main input that governs the water level. This can also be confirmed by the water depths as shown in figure 41 below.

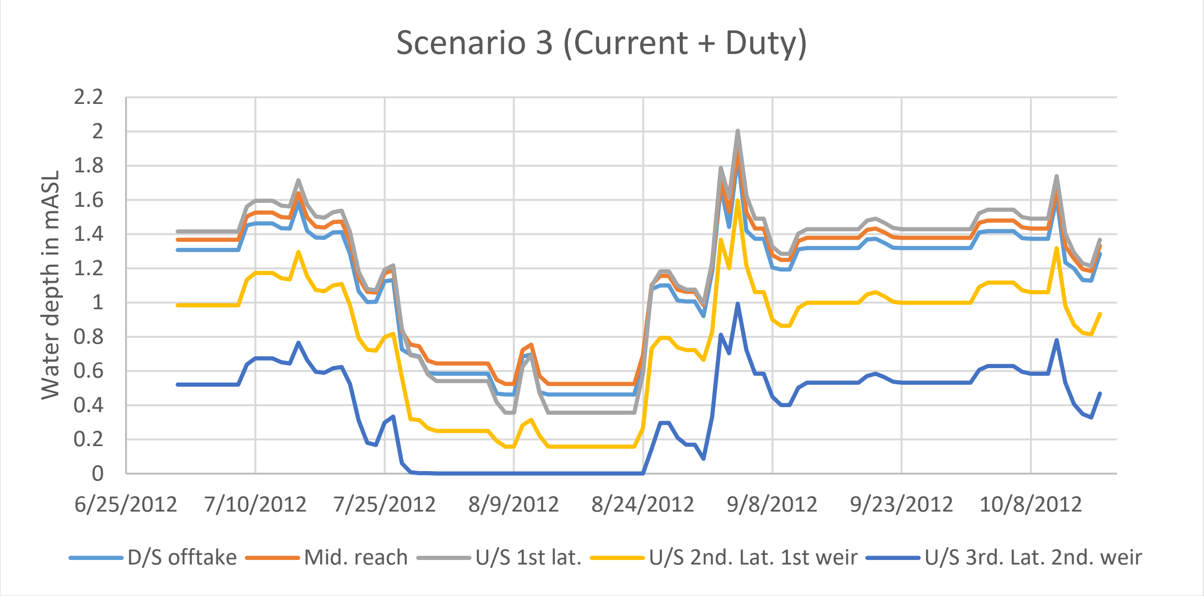


Figure 41. Scenario 3 water depths

From the graphs above, we can notice there are several locations with zero water recorded. This is related to areas that have used rainwater instead of irrigation, thus irrigation was not needed during that period. This is clearly reflection in the section of the water budget in chapter 3. Also, table 18 in appendix C shows the recorded measurements of the discharges entering the minor canals.

Scenario 4: Operation based on the Actual Crop Water requirement under current situation:

This scenario is the closest to representing the current situation of Gezira Scheme. Water demands are obtained by taking the actual CWR. The actual hydraulics and characteristics of the system are used to represent the actual canal situation in the scheme.

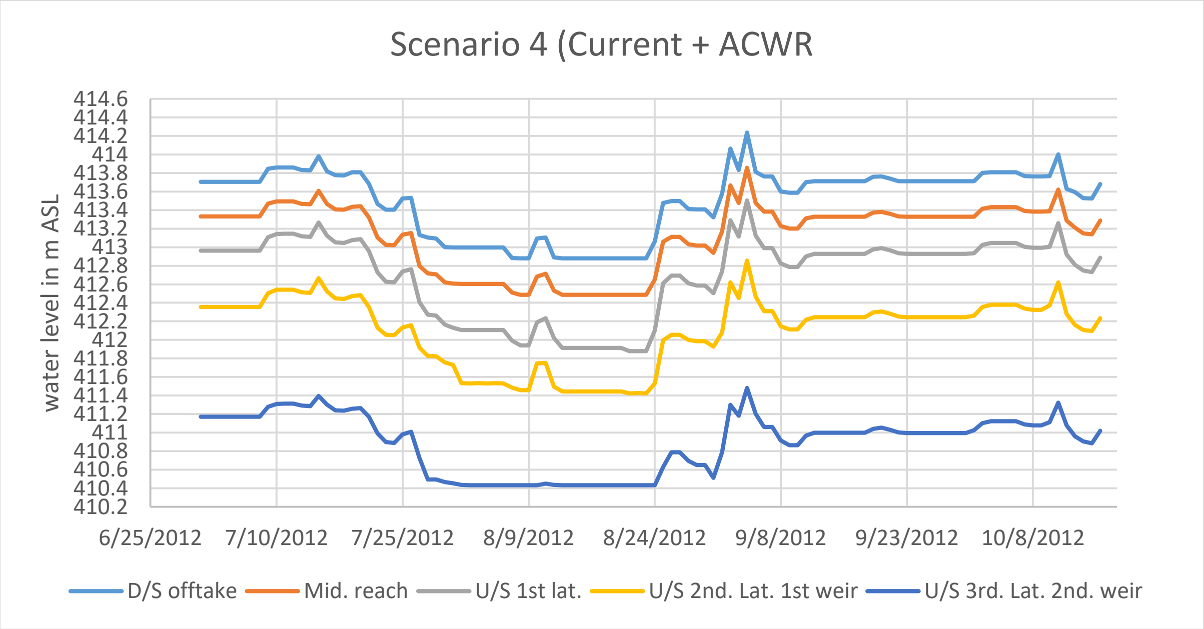


Figure 42. Scenario 4 water levels

From the above graphs, we can notice slight differences between the duty system and the actual CWR water demands on the water levels of the system. When comparing the graphs of the duty system in figure in 41 and the ACWR in figure 43, there is barely a noticeable difference between the duty system and the ACWR regarding the water levels/depths. This is elaborated with more details in the coming section of results.

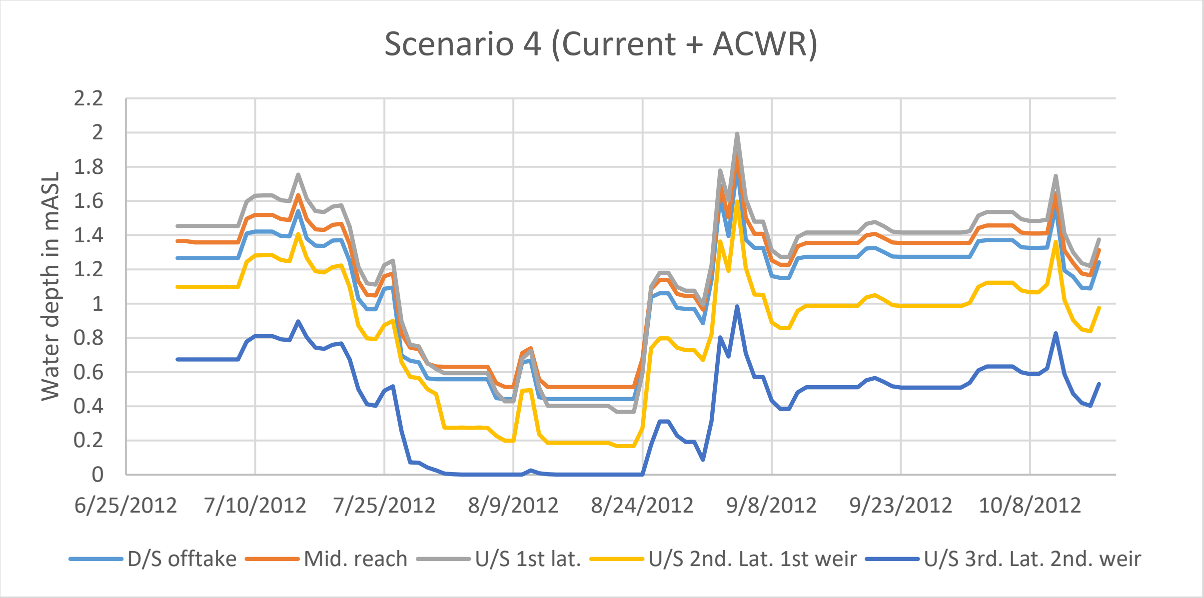


Figure 43. Scenario 4 water depths

4.6 Major Canal Results

D/S Zananda offtake

From the graph below in figure 44, we can see there is a very slight variation within the two base scenarios and the two current scenarios. Therefore, the water demand methods do not seem to influence the water levels in this location. Although there is an increase in the water levels between the design and the current settings, yet these new water depths still fit in the current canal cross-sections. The maximum water depth recorded is less than 2 m, hence even when having this maximum water depth there is a free board of 1 m in the canal section. In addition, when desilting maintenance is carried, the removed volume of the silts from the canal bed is placed on the shoulders of the canals increasing the height of the canal’s shoulders.

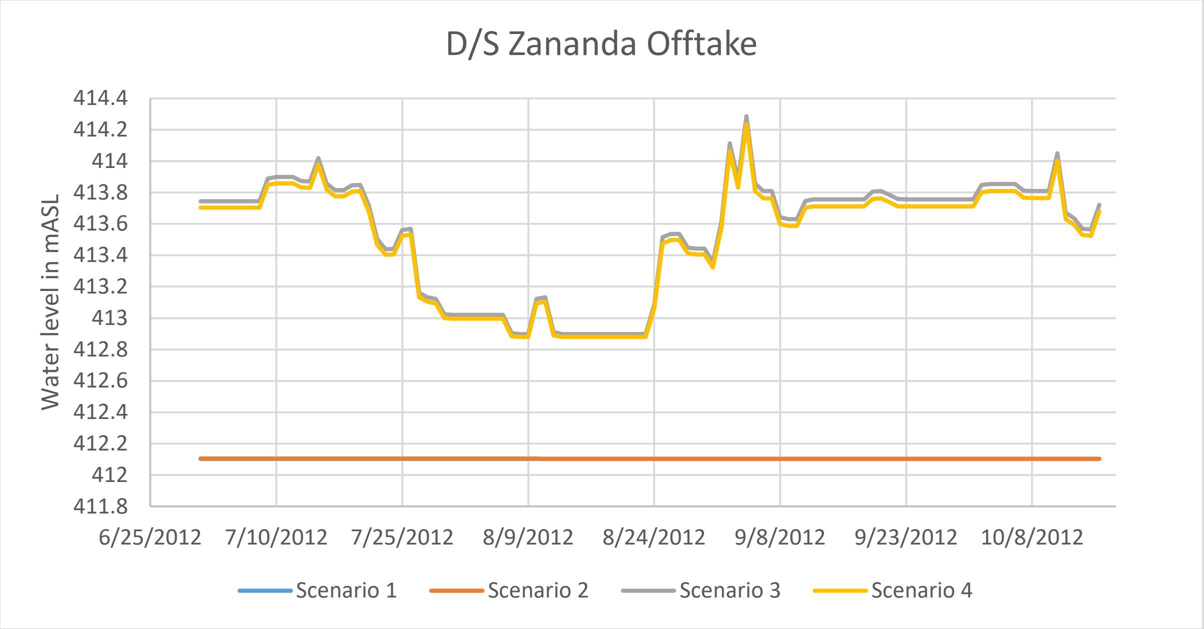


Figure 44. Water levels under different operation scenarios at D/S of Zananda offtake

Mid-Reach of first reach

The mid reach location is about 3.7 km from the offtake, there is also no variation in this location. They are almost identical for each setting (design and current).

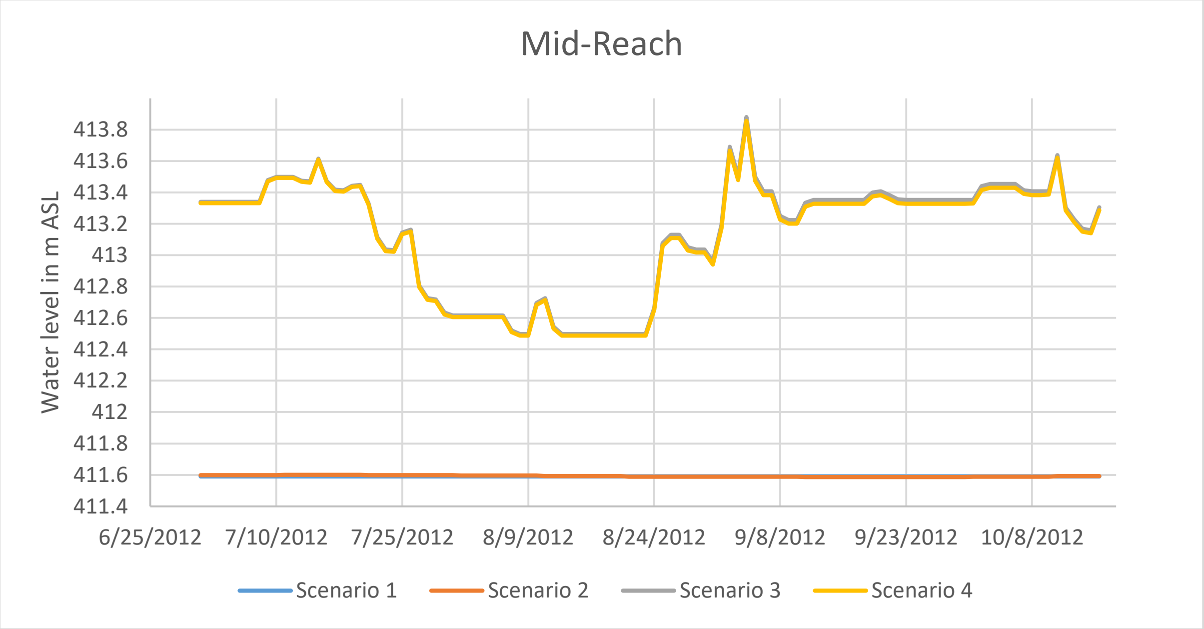


Figure 45. Water levels under different operation scenarios at Middle of Zananda first reach

U/S first lateral offtake

U/S of the first lateral offtake does not show any significant variation as well.

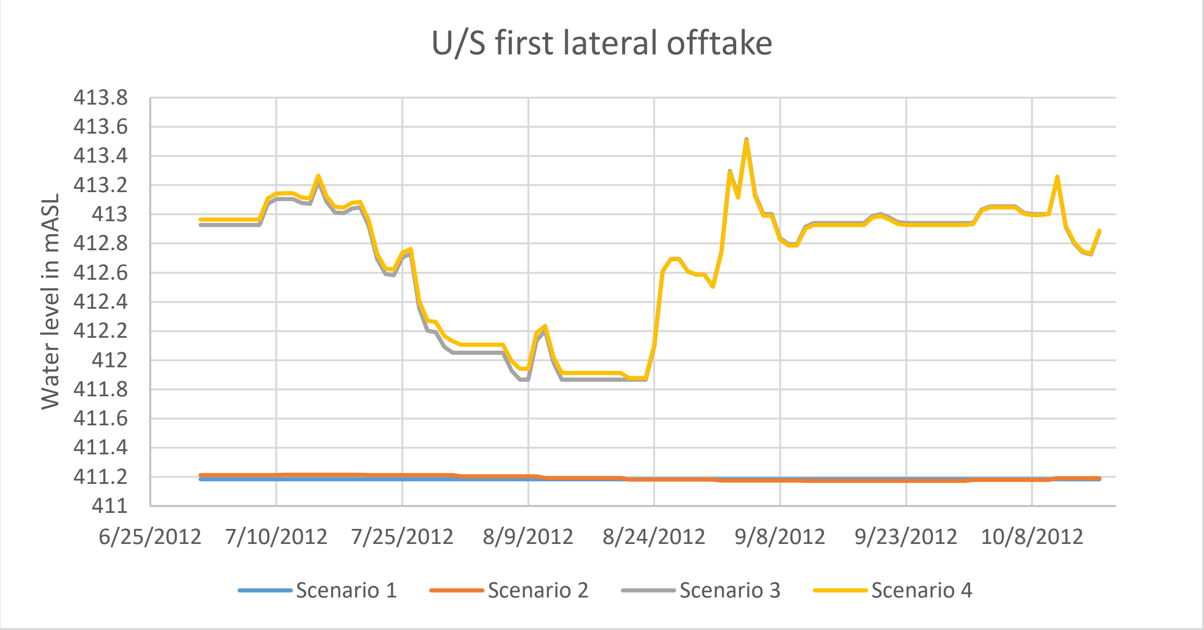


Figure 46. Water levels under different operation scenarios at U/S first lateral offtake

U/S second lateral offtake and first weir

In the location upstream the first weir, there is a variation of in water levels between the scenarios. It can be noticed at the beginning of the season. For the base model, the change is minor, while for the current situation setting, it is about 15 cm between the duty method and the actual CWR method.

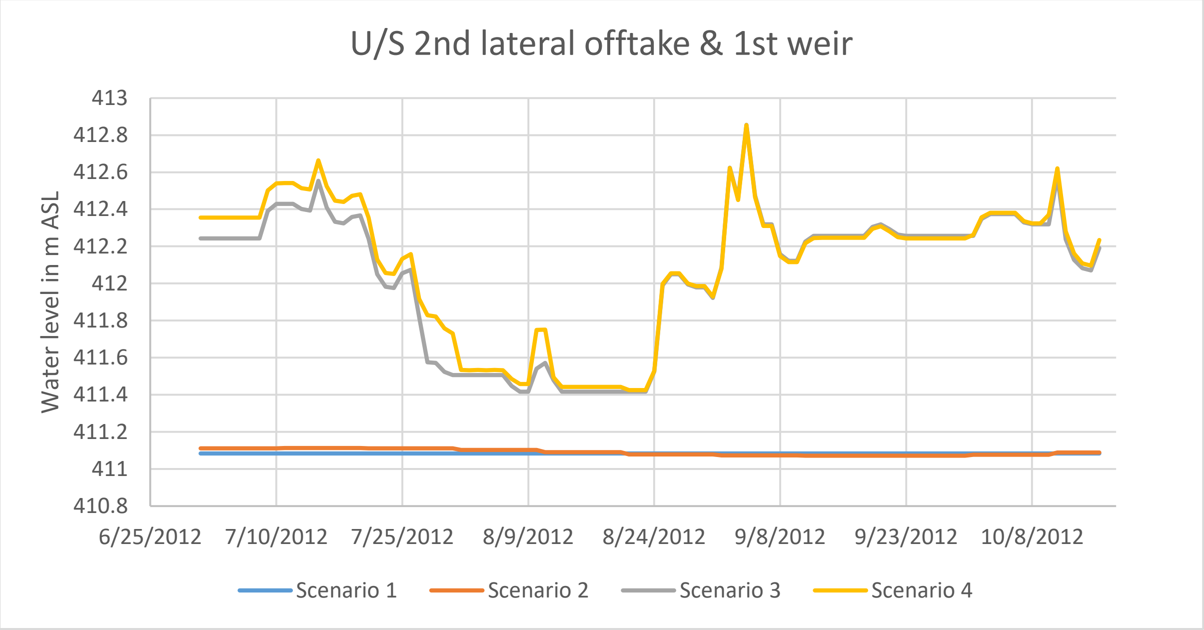


Figure 47. Water levels under different operation scenarios at U/S second lateral offtake and first weir

U/S third lateral offtake and second weir

The location is upstream the second weir. The change in water level between the water demand methods for the current model setting can be clearly seen. Especially during the first period of the season, the variation is higher. For the design model setting, there is almost no variation.

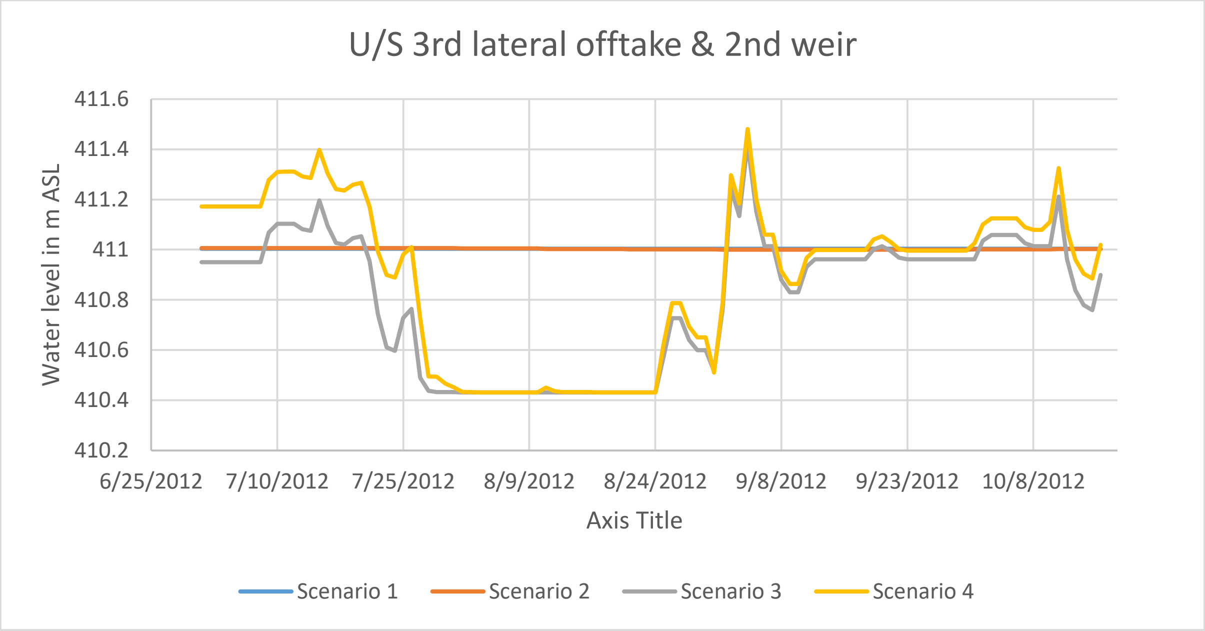


Figure 48. Water levels under different operation scenarios at U/S of third lateral offtake and second weir

Overall, it seems that for those locations that are far upstream from the weirs, there is almost no variation in the water level between the duty system and the actual crop water requirement methods when modelled within the same system setting (Design setting and current setting). For the locations near the weirs, the difference is noticed more clearly. The location upstream the second weir shows more variation than the location upstream the first weir. This is can be related to the amount of water that is available in the first reaches. As we go downstream, the system more outflow is taken from the system, hence any additional subtract can be noticed. This can be noticed from the water discharge graph shown below as an example for scenario 4 (13-July-2012).

There is a rather huge difference between design and current canal system settings, to the extent that it is questionable that the current canal system can deliver the design discharge.

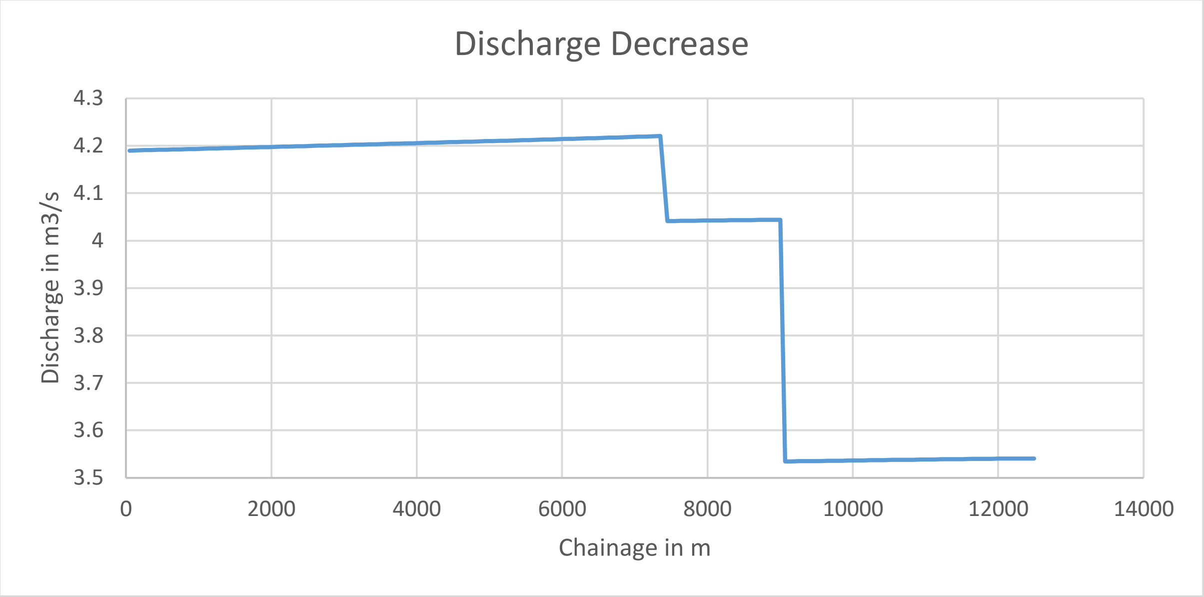


Figure 49. Discharge variation throughout the Zananda Major Canal

Effect of weir settings

Scenario 4 has been taken to investigate the influence of weir settings on the systems water levels and operation. It is the closest scenario to the current operation status. The weir settings were put at lowest, average and highest crest levels, according to the records available from summer season of 2012 as shown in table. Table 18 in the appendix shows the weirs crest level records for the whole season. From the first three graphs 51-53, there is almost no change in water levels at these locations due to change in the weirs crest levels downstream of them.

Table 14. Crest levels settings of the first and second weirs in Zananda major Canal

	First weir at 9.1	Second weir at 12.5
Minimum mASL	411.35	410.4
Average mASL	411.6578	410.5223
Maximum mASL	411.75	410.9

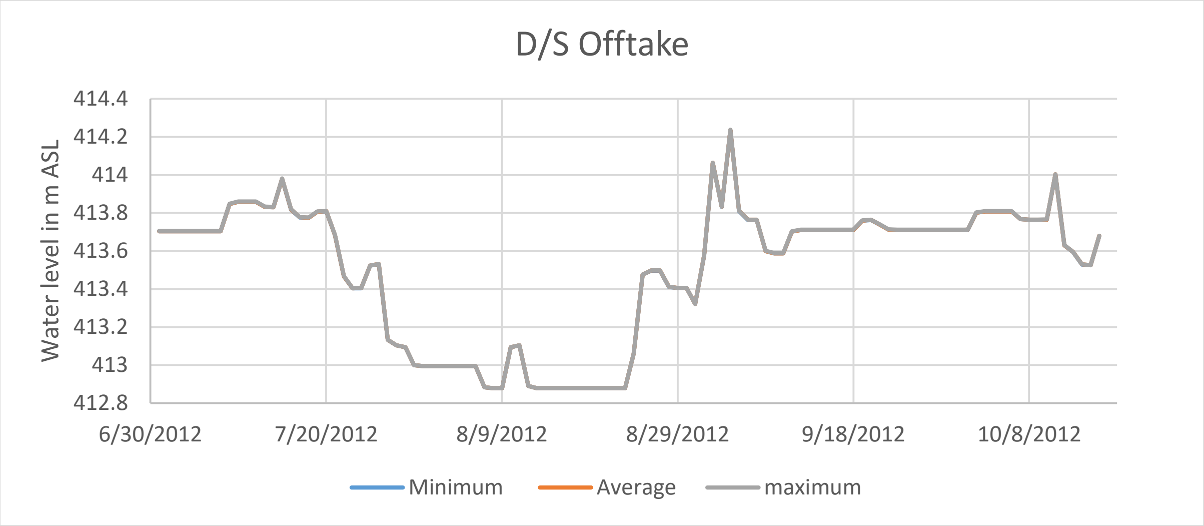


Figure 50. Water level variation at D/S of offtake

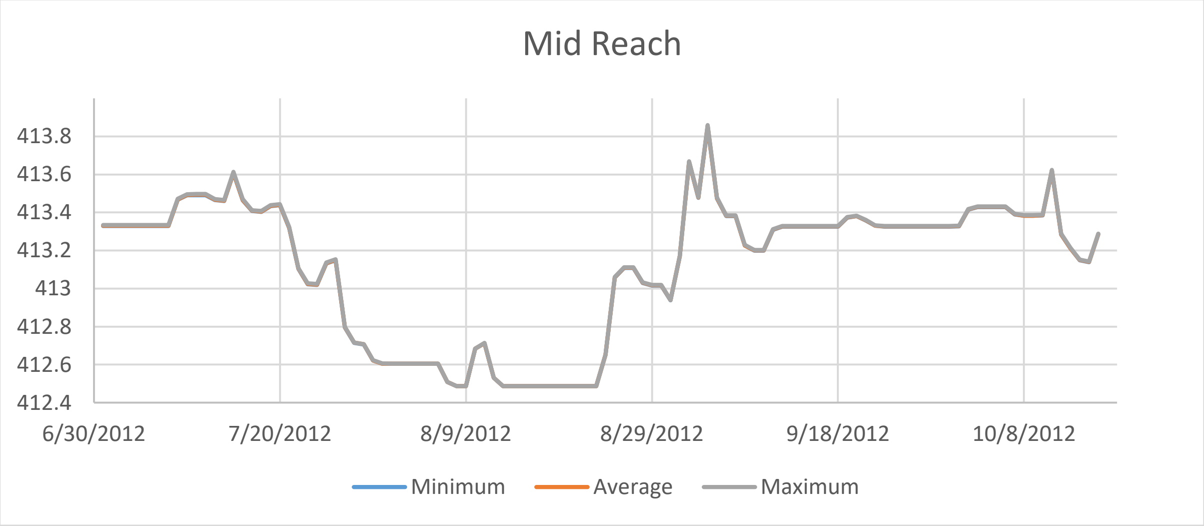


Figure 51. Water level variation at Mid reach

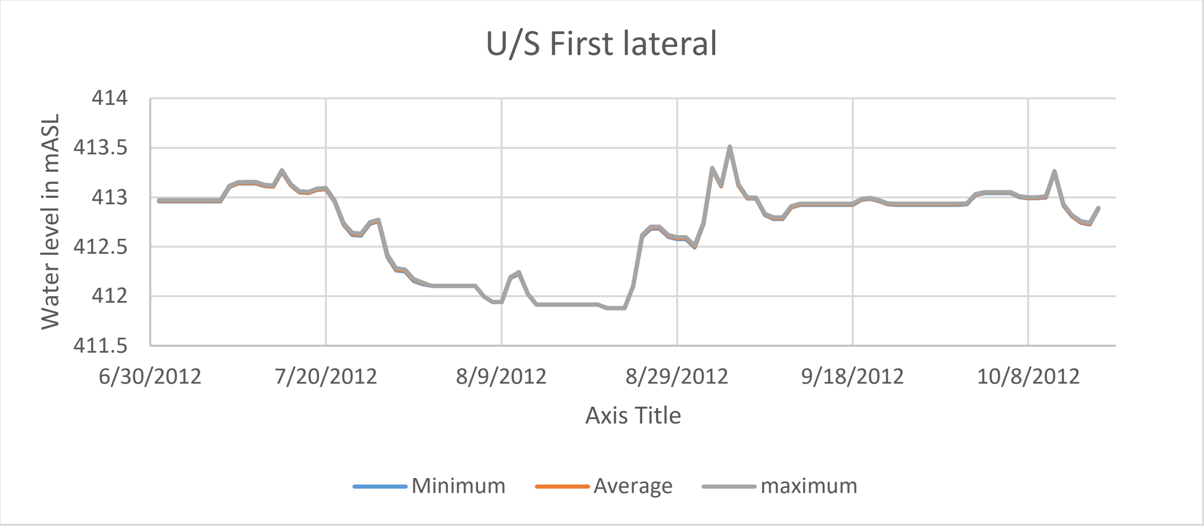


Figure 52. Water level variation at U/S first lateral outflow

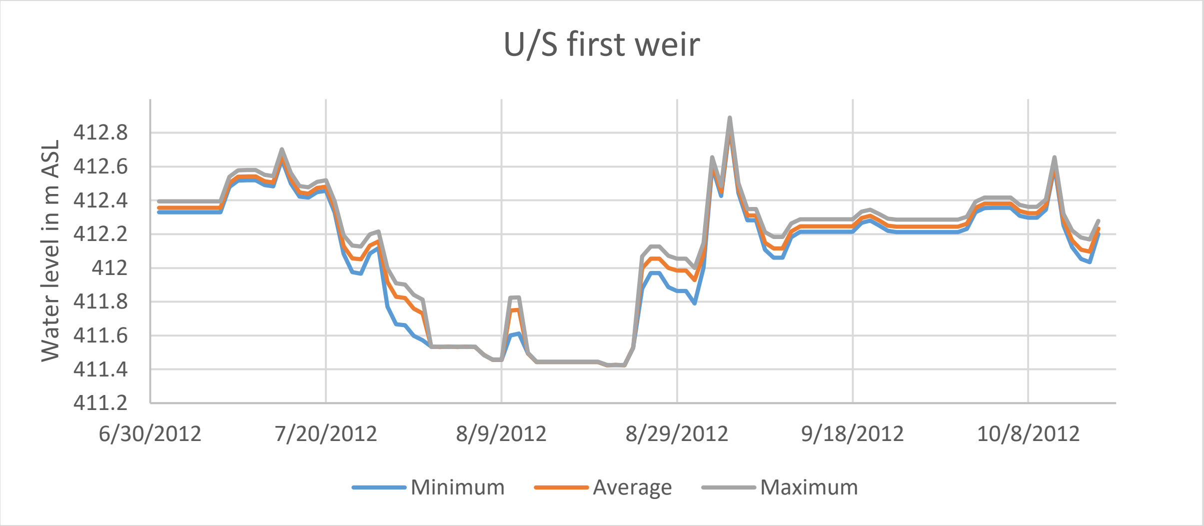


Figure 53. Water level variation at U/S first weir

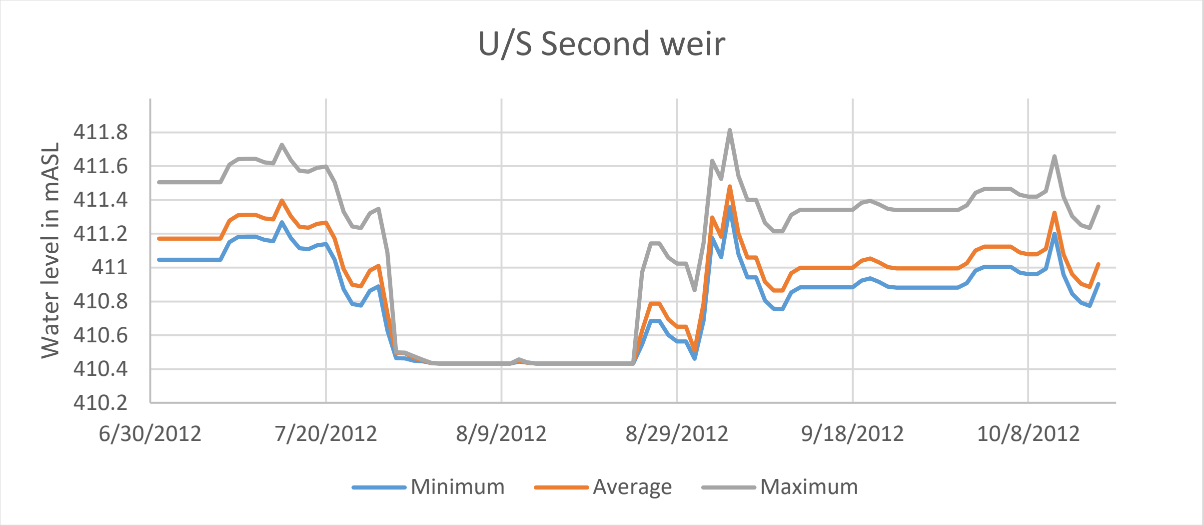


Figure 54. Water level variation at U/S second weir

The last two graphs 53 and 54 represent the location U/S of the first and the second weirs respectively. The water levels variation can be noticed as we go downstream. It is minor upstream the first weir and larger in the second weir, where it can reach up to 50 cm difference between the minimum setting and the maximum setting.

4.7 Toman Minor Canal:

By now, it is well known to the reader that the initial design of the minor canals in the Gezira system were to be operated as storage canals. The operation of the minor canals under the night storage system was conducted by closing the offtakes (field outlet pipes) and control structures during night (6 pm to 6 am) and reopening them during the day. This strategy increased the water level in the canal, hence have more head for the flow to enter into Abu Ishreen. In recent years, this operation strategy has been abandoned and minor canals were turned into continuous conveyance canals. In this section, the two systems are modelled to see the response of the system under the two operation strategies.

The canal is divided into 4 reaches, with actual cross-sections that are defined at the beginning and the end of each reach. The design characteristics of the Toman Minor Canal are presented in table 14 below. Yet, in this setup, the current status will be used for modelling the minor canal, unlike has been done in major canal. For the major canal, we wanted to see all the possible scenarios, but here it is more realistic to model the different operation strategies under the current situation of the canal. The cropped area with specified crops is shown in table 15. The actual CWR approach (Farbrother, 1974) was carried for determining the water demand. The inflow coming from Zananda major canal has been used as boundary condition for Toman minor canal.

Table 15. Design Characteristics of Toman Minor Canal (MoIWR)

Reach	Bed width (m)	Side slope (-)	Bed slope (-)	Length of the reach (m)
1	2	2	0.0002	1200
2	2	2	0.0002	1800
3	1.5	2	0.0001	1700
4	1	2	0.00025	1300

Cross-sections

In this section, the cross-sections of Toman minor canal that are used in modelling are presented. The actual cross-sections are compared to the design cross sections at five locations, as shown on figure 57 below. The same locations will also be used to present results of water levels and depths.

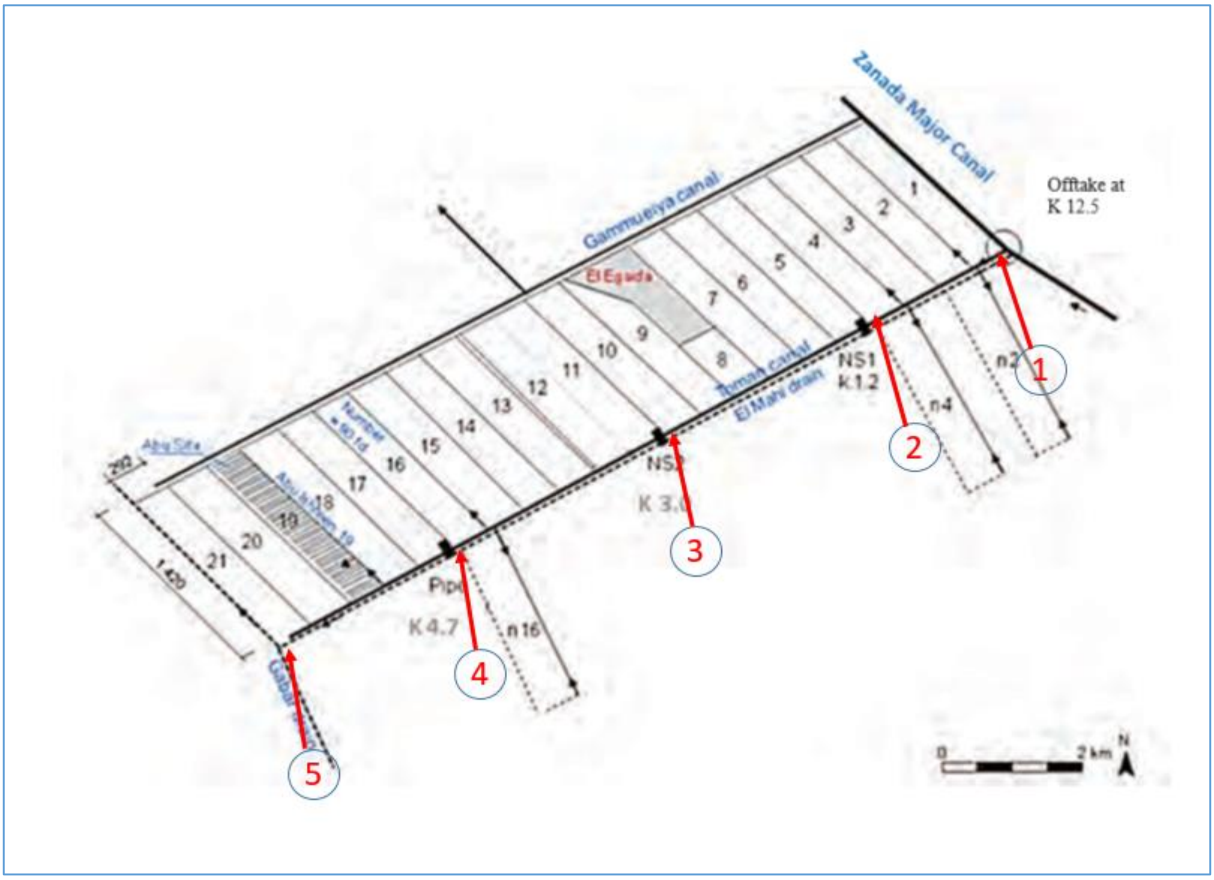


Figure 55. Location where results of water levels and depths are shown (Aalbers, 2012)

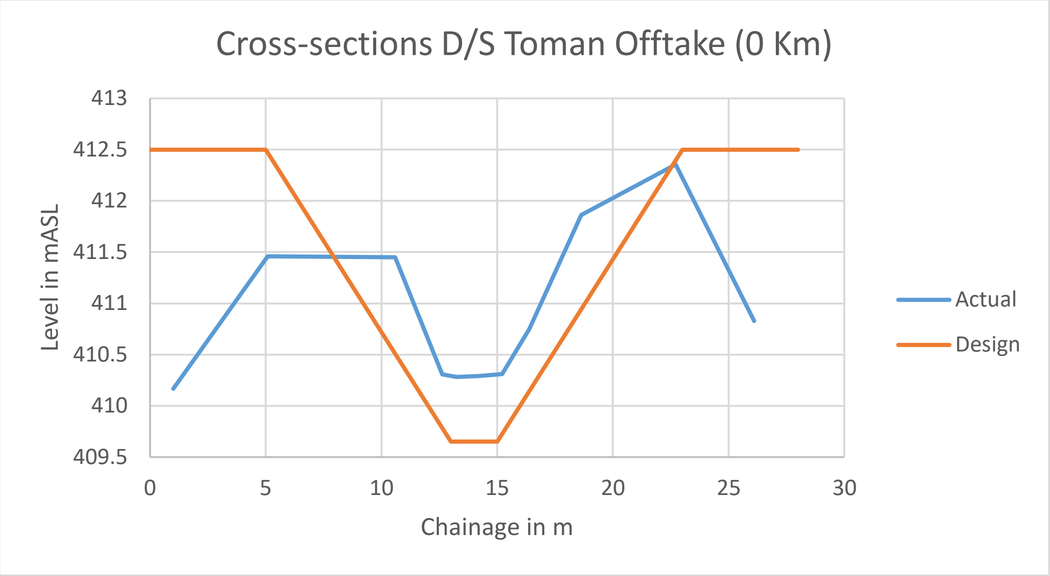


Figure 56. Cross-sections of Toman minor canal at 0.0 Km

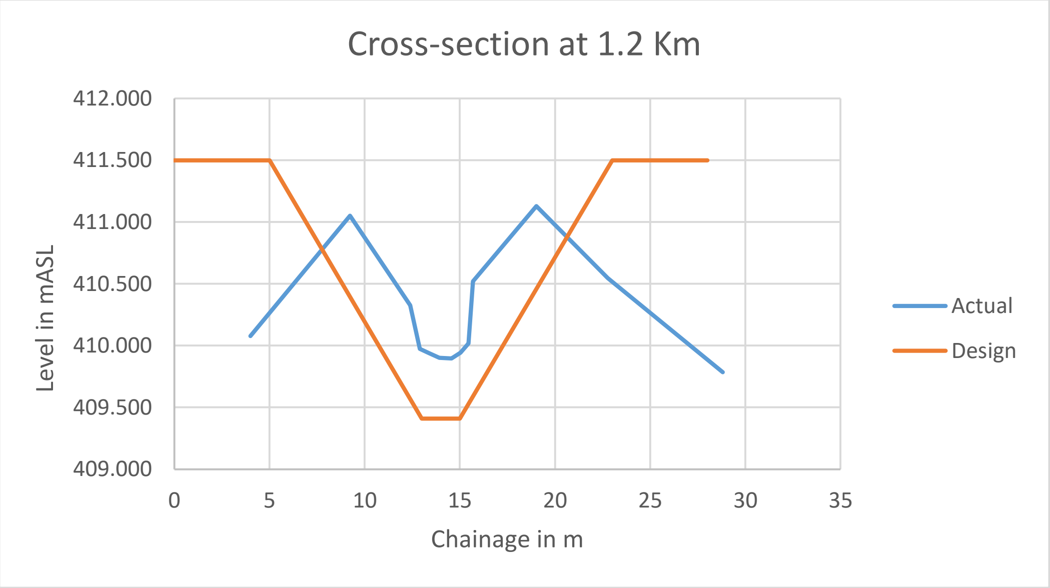


Figure 57. Cross-sections of Toman minor canal at 1.2 Km

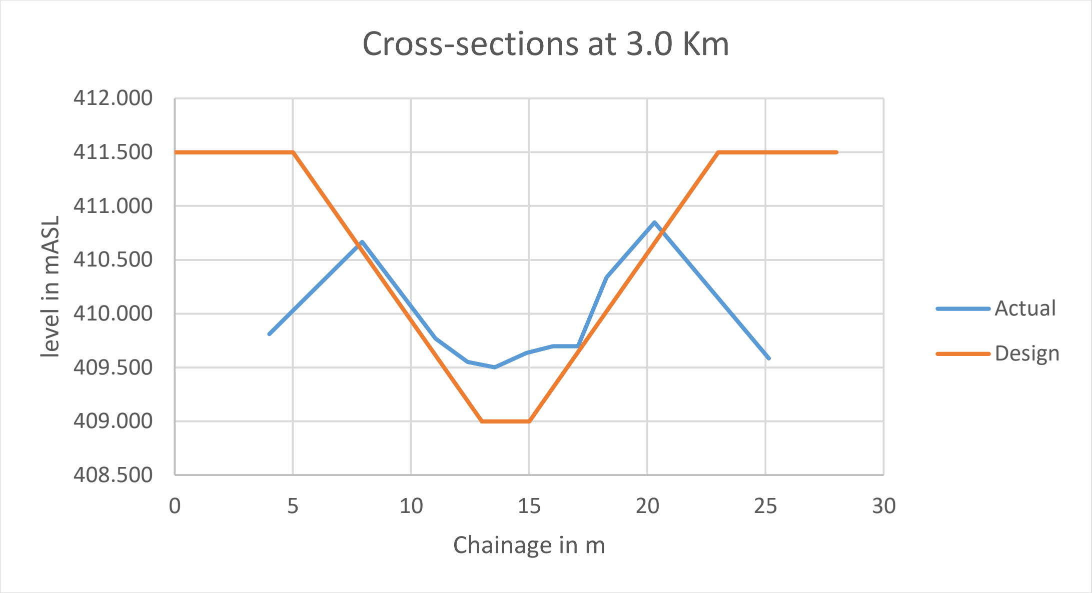


Figure 58. Cross-sections of Toman minor canal at 3.0 Km

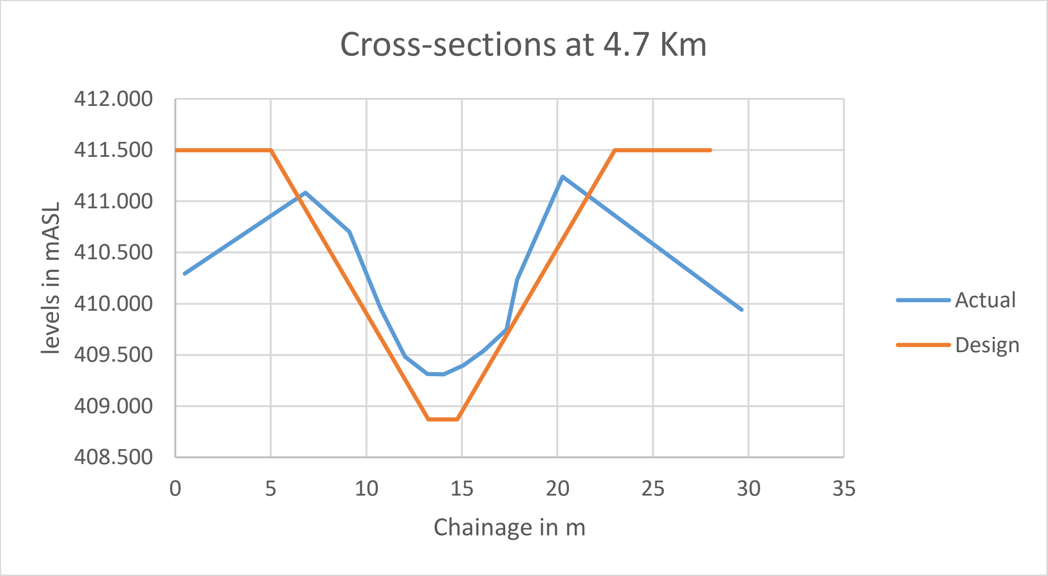


Figure 59. Cross-sections of Toman minor canal at 4.7 Km

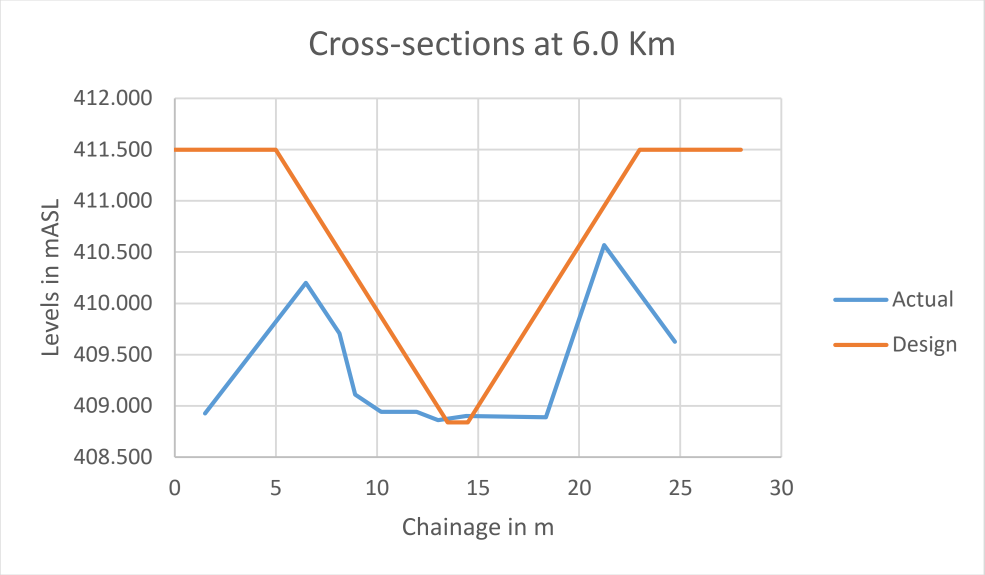


Figure 60.Cross-sections of Toman minor canal at 6.0 Km

Scenario 5: Operation under Continuous Flow (Current Status – Actual CWR):

In this scenario, the simulation is based on the type of operation flow in the minor canal. As stated above, the first scenario is setup using the continuous flow operation of the minor canal under the current status of the system. For the water demand, the actual CWR is imported. Due to limited details about the setup of Abu Ishreen for each Nimra, and for simplification, the Nimras for each reach were summed and inserted as one outflow lateral discharge. Figure 62 below, shows a schematic longitudinal profile of Toman minor canal with its water level profile.

Table 16. Cropped area per Nimra (ha) in Toman Minor Canal system in 2012

Nimra	Sorghum (ha)	Groundnut (ha)	Vegetables (ha)	Cotton (ha)	Total (ha)
1	35	0	1	0	36
2	Fallow				
3	14	8	12	0	34
4	Fallow				
5	29	1	0	0	29
6	10	1	2	0	13
7	12	2	10	0	24
8	1	3	10	0	14
9	22	0	0	0	22
10	Fallow				
11	27	7	2	0	35
12	Fallow				
13	29	7	0	0	36
14	Fallow				
15	21	8	0	0	29
16	10	5	0	0	15
17	Fallow				
18	Fallow				
19	7	10	3	2	22
20	32	0	0	0	32
21	34	0	0	0	34

Total	283	51	40	2	376

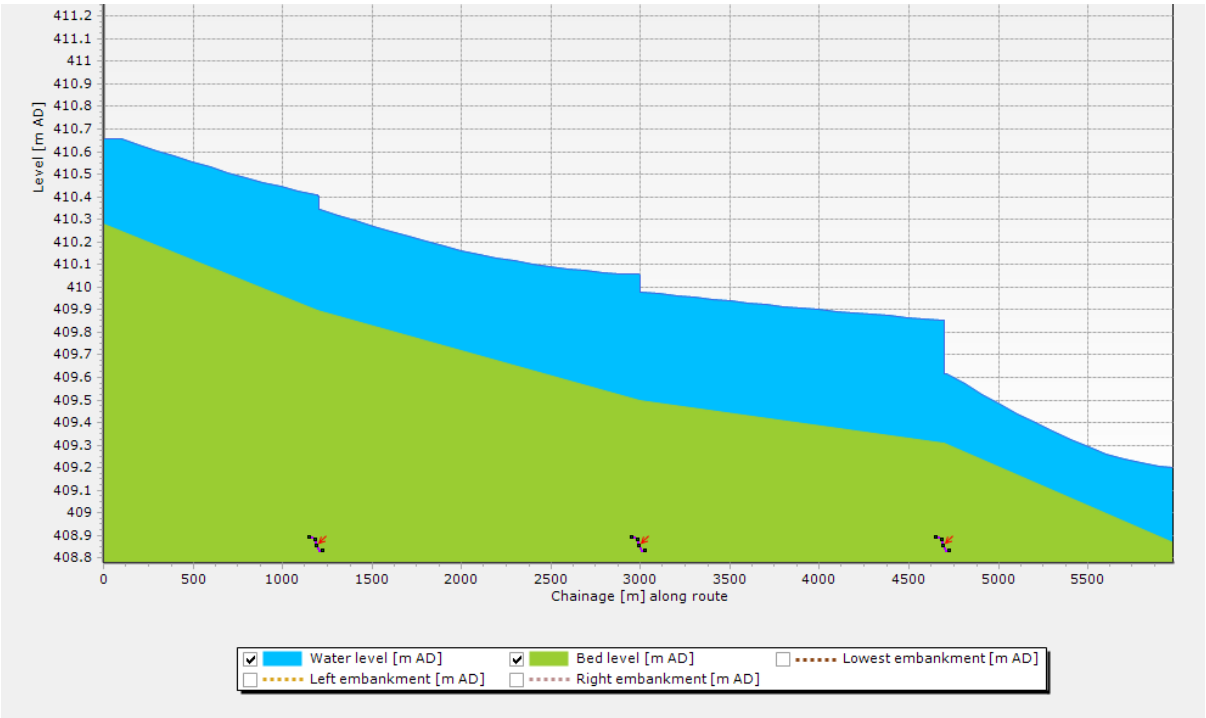


Figure 61. Longitudinal profile of Toman minor canal

From the graphs 63 and 64 below, we can notice the fluctuation water levels at different locations. This is linked to the inflow variation at the offtake, which is taken as the release coming from Zananda major canal. This confirms the previous remark that fluctuations are linked strongly with the inflow variation.

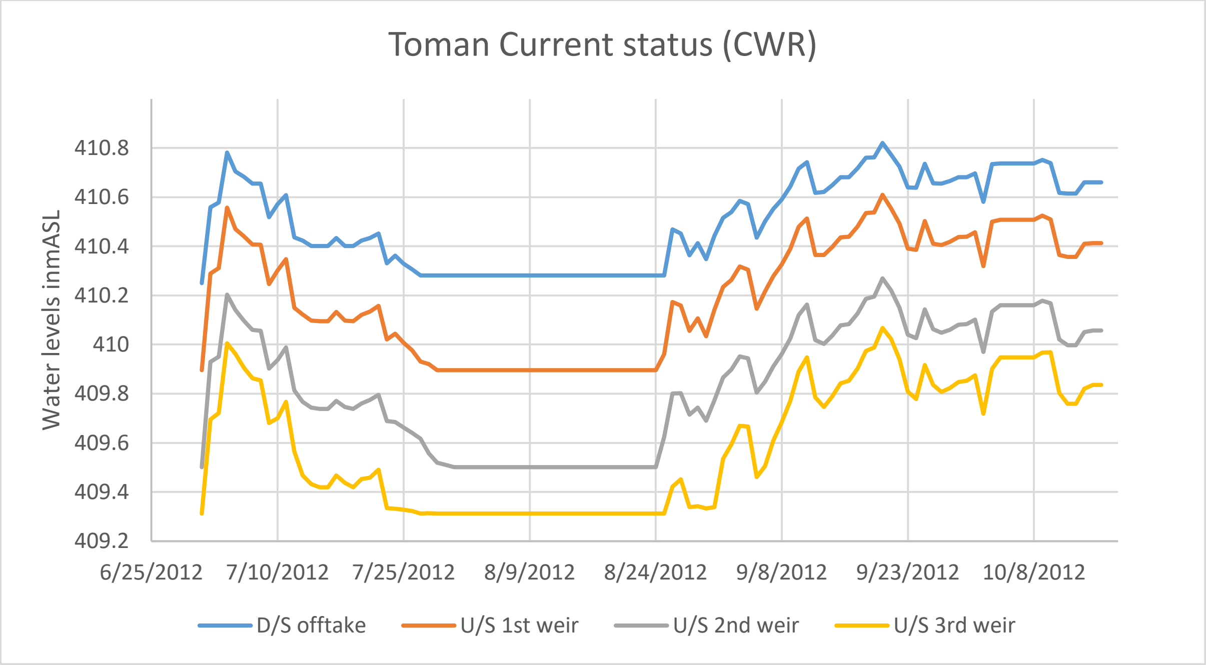


Figure 62. Water levels of Toman minor canals under continuous flow regime

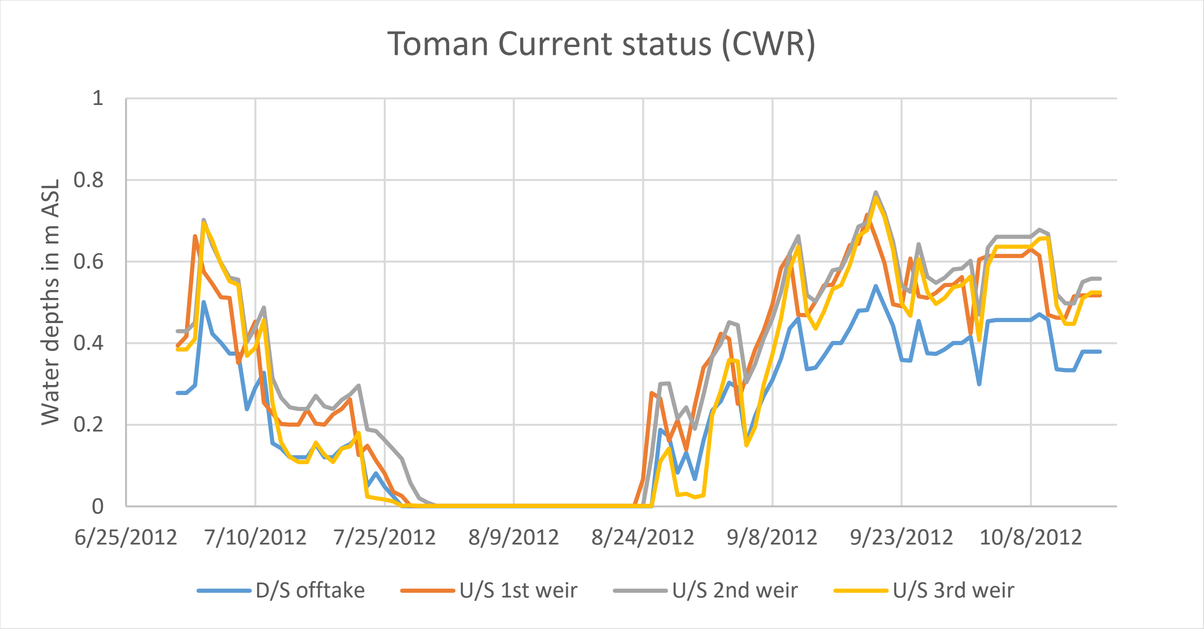


Figure 63.Water depths of Toman minor canal under continuous flow regime

Scenario 6: Operation under Night Storage Flow (Base Model-Actual CWR):

In this scenario, we wanted to investigate the old night storage system, that has been used before the continuous flow. The change will be made in the lateral discharges operation, which will be null during night, and released during the day. The time step has been changed into a 6-hour time step to notice the difference in water levels between day and night. For this scenario, the design characteristics and discharges were used. The fluctuations of the night storage system can be seen clearly in this scenario. The difference does not exceed 20 cm in all locations, which aligns with the initial design of the night storage system.

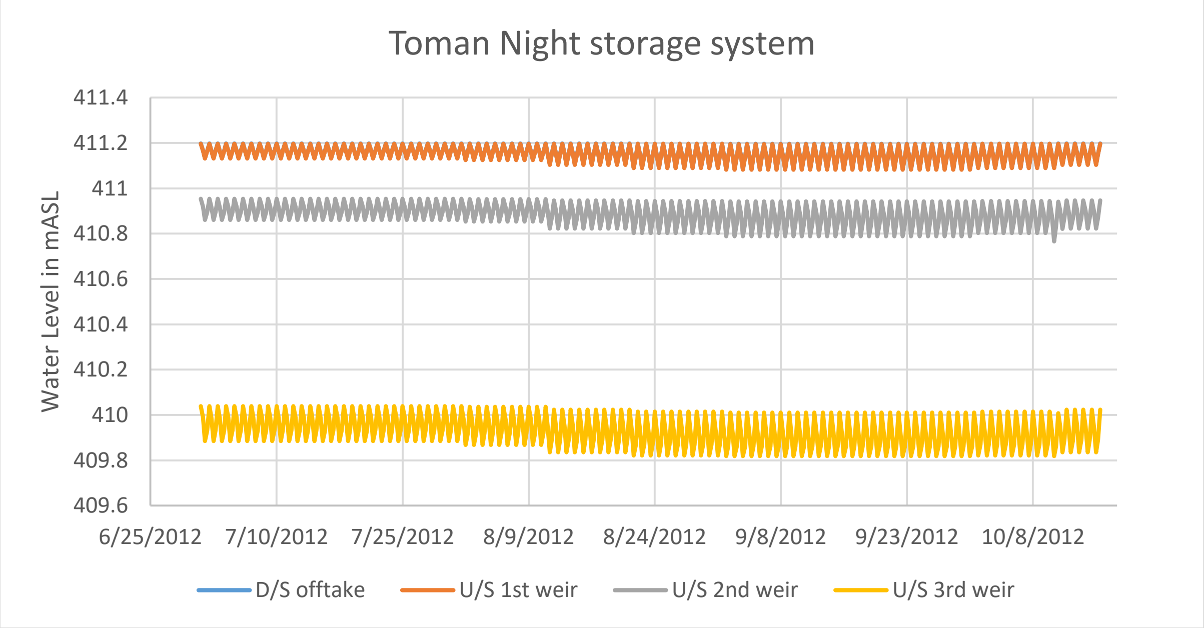


Figure 64. Water level fluctuation at Toman minor canal under the night storage system

4.8 Combined System

In this phase of modelling, we want to investigate the implementation of the new water demand approach, which is determining the water crop requirements using real time remote sensing methods. These methods provide the water demands on real time basis, and not on a predetermined scheduled basis as has been implemented in the past two approaches, the duty and the Farbrother approaches. The whole system is modeled in order to study the response under different demands coming from different minor canal locations. The results will be evaluated at the offtake of the major canal, in terms of response time and change in water levels/depths.

The figure below illustrates the model setup for the combined system. Since data records was only available for Toman minor canals, we have used the characteristics of Toman minor canal to represent the other minor canals of Gimiliia (Minor -1), and W/Elmahi (Minor-2). It was found these three canals, Toman, Gimillia, and W/Elmahi, have average flow releases of 0.24, 0.21, 0.22 m^3/s respectively. Therefore, it was convenient to replace them with the settings of the Toman minor canal, while keeping the other minor canals as negative lateral sources.

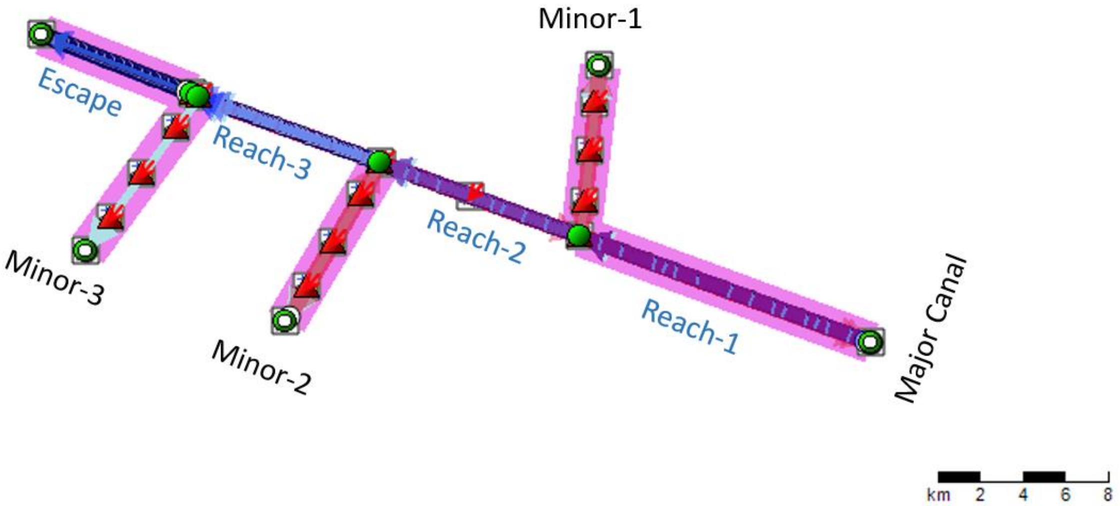


Figure 65. Model Setup for the combined system

Scenario 1: Abstraction from Minor - 3 at the D/S reach of Zananda Major canal:

For this scenario, the abstraction from minor 3 was increased suddenly for 24 hours, from 0.31 m^3/sec to 0.6 m^3/s, and then decreased to its normal discharge. It is important to mention that the discharges modelled are within the carrying capacity of the canal, as the maximum recorded discharge in the current setting was 0.76 m^3/s (See table 17 in appendix C). This was also confirmed in the model, by assuring the water depths did not exceed the ground levels of the canals shoulders (taking into consideration the free board limits) as shown in the figure below.

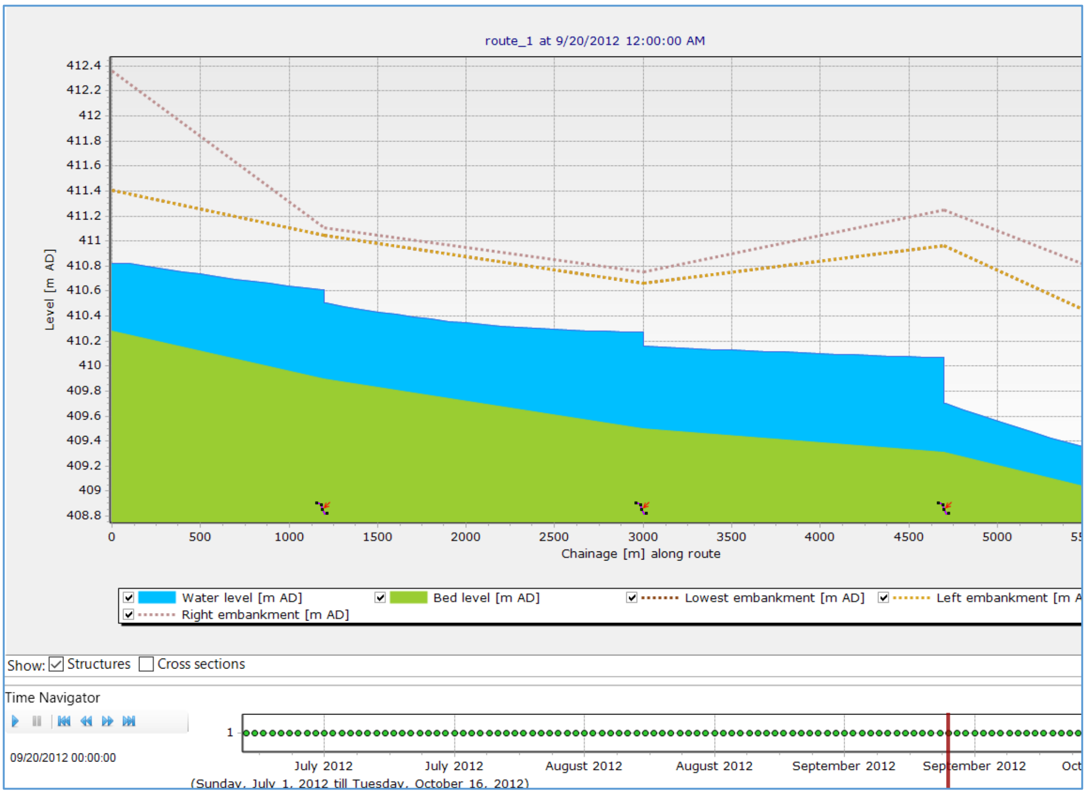


Figure 65. maximum water depth responding to 0.76 m3/s on 20/09/2012

The effect of the increment was seen immediately upstream of the minor offtake in reach 3 (see figure 67), yet it did not go beyond the second weir structure of the major canal. Therefore, the effect was only sensible on reach-3.

From graph 67 below we can notice there a slight change in the water depth at the U/S of the reach. Yet, it is an immediate response when compared to the time of increase in demand.

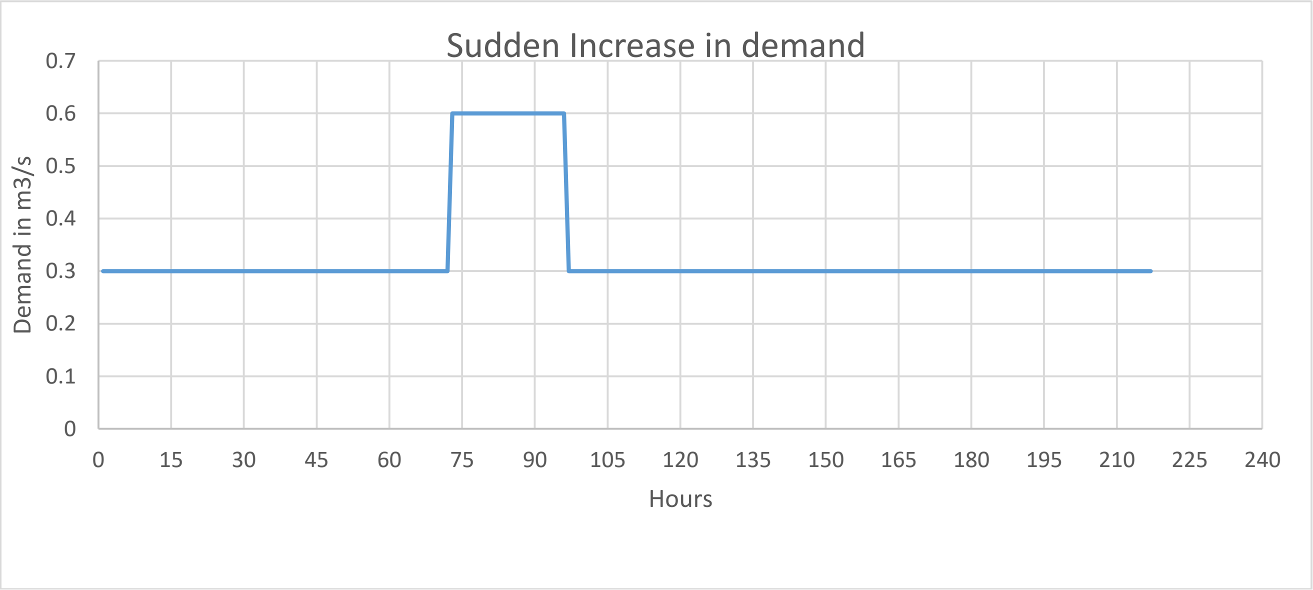


Figure 66. Sudden increase in water demand for 24 hrs. in minor canals

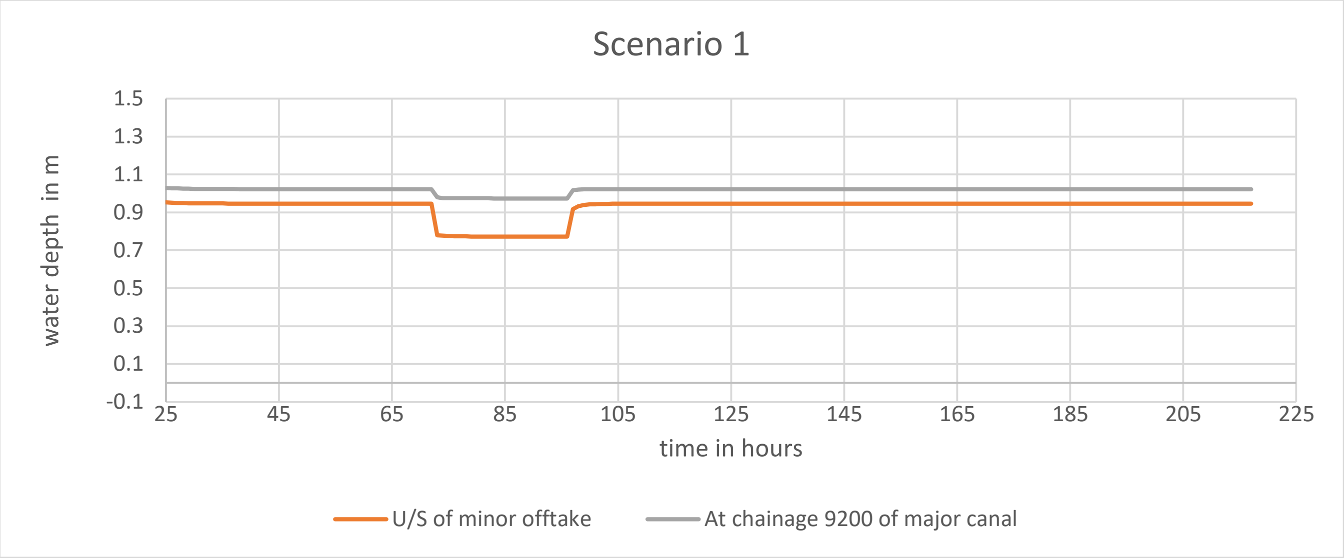


Figure 67. Response of system to sudden increase in minor 3

Scenario 2: Abstraction from Minor - 2 at the middle reach of Zananda Major canal:

The same approach was implemented for minor-2. Since there is no weir upstream this offtake, we want to investigate to what limit could the effect be seen. The graph below shows two locations: the right U/S of the offtake, the second the beginning of the second reach. The further away from the offtake the less the variation in water depth is noticed. There is a slight variation in the water depth at the beginning of reach-2. The difference in water depth between the two locations before and after the abstraction is about 4 cm, while during the abstraction it is about 6 cm.

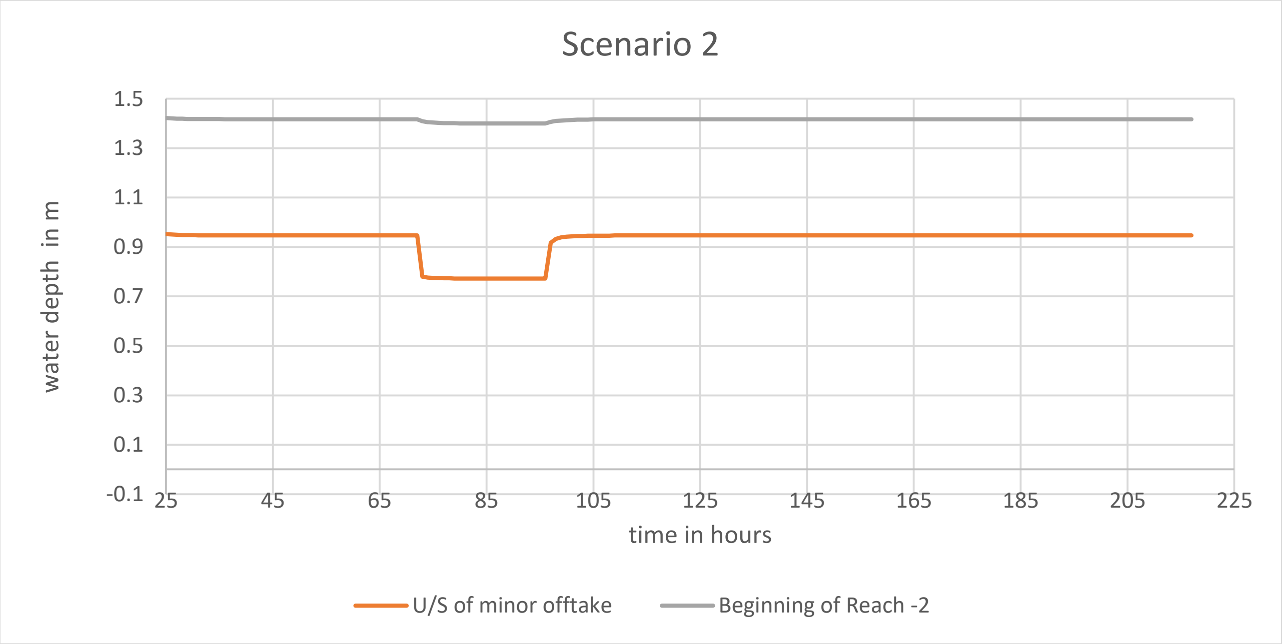


Figure 68. Response of system to sudden increase in minor 2

Scenario 3: Abstraction from Minor - 3 at the U/S reach of Zananda Major canal:

For this scenario, the abstraction of minor-1 was increased following the same process as the previous scenarios. The water depth was evaluated at the right U/S of the offtake and at the beginning of reach -1. Again, the water depth variation at the offtake is large compared to further location (beginning of the reach). Also, in this scenario the water depths variation was not linear as in the past two scenarios. This is seen at the beginning of the abstraction and at the end.

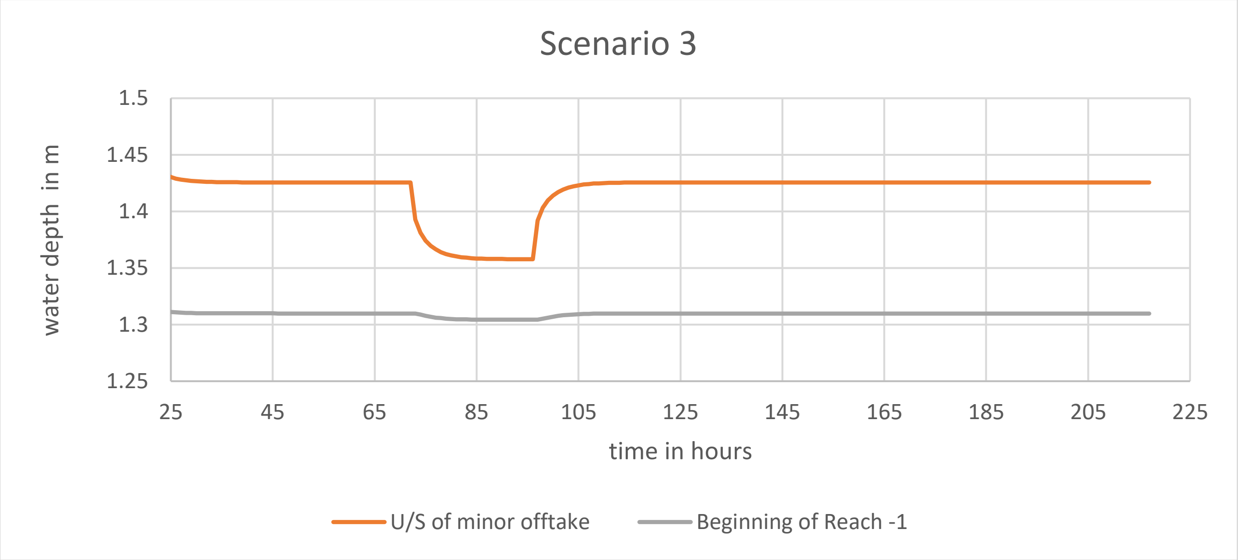


Figure 69. Response of system to sudden increase in minor-1

Scenario 4: Abstraction from all minor canals at the same time:

In this scenario, all minors will withdraw water at the same time. The graph below shows the 6 different locations regarding each minor canal. We can notice that the water depths at U/S reach 2 and U/S offtake minor 1 are almost identical, where the yellow line is almost covered by the U/S reach 2 line. This is because there is no weir at this location to separate the reaches, hence the change in water depth is almost identical. The effect of weirs is noticeable here, which was also described in the characteristics of the moveable weirs structures used in the Gezira scheme, they are not affected by downstream conditions. It is also noticed that downstream locations show higher variation in water depths than upstream locations.

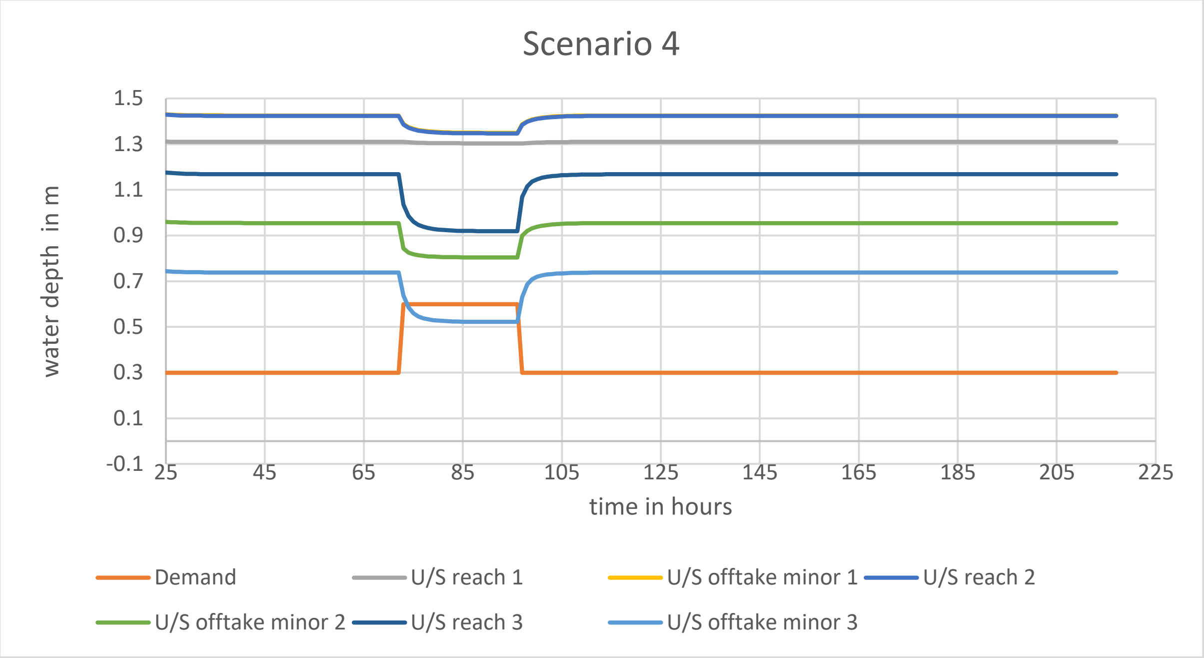


Figure 70. Change in water depth at different location responding to change in demand

5 Discussion and Conclusion

- From the results of modelling, we can notice that in general the most effective factor in the system is the amount of inflow entering. In the first two scenarios of the major canal base model, the water demand methods, whether it was the duty system or the actual crop water requirement, did not differ much as shown by the water levels. There was a slight difference in the U/S of the first and second lateral in the month of September, but it is a magnitude of few centimeter (less than 5 cm).

- The effect of the inflow can be seen clearly in the setting of the current status of the major canal, where water levels fluctuations are present throughout the system. Still the effect of the water demand methods is negligible.

- The effect of sedimentation is noticed in the first reach of Zananda major canals where the difference of the water levels between the base setting and current setting range between 0.8 to 2.0 m. The time difference between the design and the current cross-section is more than 90 years, therefore it is not surprising to have this amount of bed level variation between the design and current status. This is also confirmed with other studies carried about sedimentation in the Gezira.

- The effect of the over-digging can be noticed in the second reach, in the location upstream of the second weir, where we can see the water level of the base setting and the current setting are similar or the current situation is even less, although there is sedimentation in this reach as well.

- From the weir setting analysis, we can notice that, in general, the upstream sections that are far from the lateral outflows and weirs are less affected by the change in weir crest level settings, while locations close to the weir are more sensitive.

- In Toman minor canal, the continuous and the night storage system show water levels that are within the design limits of the system – even for the actual canal settings. The fluctuation of the opening and closing during the night storage system can be noticed clearly compared to the continuous flow. Although the night storage system shows daily fluctuation, it still reflects the initial intention of the storage in order to raise the water level for better command for Abu Ishreen.

- In the combined system, when inserting sudden increases in the water demands, there was a rapid response within the system for a 24-hour demand change. The change in water depths occurred within the time step of one hour in all scenarios. We can relate that to the longitudinal profile of the major and minor canals we have taken for modelling. Zananda major canal is 12.5 km, while there are other major canals in the Gezira system that are much longer, hence their response might differ when compared to short major canals. Toman minor canal is 6 km.

- Zananda major canals is considered to be at the upstream system of the Gezira scheme. As can be seen from the scheme layout, it is flowing from K57, which marks the first junction point in the system. This means it is 57 kilometers from the Sennar headworks. This distance has not been accounted for in the modeling, but it is important to bear in mind that, even if the system responded rapidly within the boundary of our major canal system, still this response might be noticed a bit late when taking the main canal into consideration. It also means that Zananda major might be preferentially located in the Gezira, compared to many other major canals.

- As conclusion regarding the real time remote sensing methods, the Zananda system has showed rapid response, hence meeting the CWR within a short time frame might be feasible in Zananda and Toman minor canals, assuming the water is readily available at the offtake of the major canal and an adequate operation of the control structures.

- The remote sensing approach might also improve in the operation management of the scheme. The flow of the indenting system starting from the field inspectors passing through the sub-division engineers and ending at the dam takes a lot of time, communication, and effort. When using satellite data, even with some margins error, this cycle might be shortened to some extent, as it will always be needed to have some staff on the field.

6 Bibliography

Aalbers E. E., 2012. Water supply from minor canal to field level in the Gezira irrigation scheme, Sudan. Technical report. Delft University of Technology, Delft, the Netherlands.

Abdelhadi, A. W., Hata, T., Tanakamaru, H., Tada, A., & Tariq, M. A. (2000). Estimation of crop water requirements in arid region using penman-monteith equation with derived crop coefficients: a case study on acala cotton in sudan gezira irrigated scheme. Agricultural Water Management, 45(2), 203–214. https://doi.org/10.1016/S0378-3774(99)00077-3

Abdelhadi, A. W., Adam, H. S., Hassan, M. A., & Hata, T. (2004). Participatory management: would it be a turning point in the history of the gezira scheme? Irrigation and Drainage, 53(4), 429–436. https://doi.org/10.1002/ird.139

Adam, H.S. (2005) Agro-Climatology, Crop Water Requirement and Water Management. Water Management and Irrigation Institute, University of Gezira, Wad Madani, 169 p.

Adeeb A., 2006. Water productivity of food crops in Gezira Scheme, Sudan. Paper presented at the Environmentally Sound Technology in Water Resources Management, Gaborane, Botswana, 11-13 September 2006.

Ahmed, B. M. (2009). Spatial and Temporal Analysis of Evapotranspiration Using Satellite Remote Sensing Data: A Case Study in the Gezira Scheme, Sudan. Journal of Environmental Informatics - J ENVIRON INFORM. 13. 86-92. 10.3808/jei.200900143.

Ahmed, B. M., Tanakamaru, H., & Tada, A. (2010). Application of remote sensing for estimating crop water requirements, yield and water productivity of wheat in the gezira scheme. International Journal of Remote Sensing, 31(16), 4281–4294.

Al Zayed, I. S., Elagib, N. A., Ribbe, L., & Heinrich, J. (2015). Spatio-temporal performance of large-scale gezira irrigation scheme, sudan. Agricultural Systems, 133, 131–142. https://doi.org/10.1016/j.agsy.2014.10.009

Art, W., and Tyrchniewicz, A. (1995) Agriculture and sustainable development: policy analysis on the Great Plains. International Institute for Sustainable Development (IISD) Manitoba, Canada.

Babiker, A. M., Saeed, A. B., Ahmed, A. B., Mekawi, A. (2017). Effect of Reliability of Water Releases Downstream Abu Ushar Head regulator, Gezira Scheme, Sudan. Sudan Journal of Science and Technology, 18 (2), 1858 - 6716.

Bashier, E. & Adeeb, A.. (2015). Impact of changing policies on agricultural productivity: A case of the Gezira scheme, Sudan. International Journal of Sustainable Agricultural Management and Informatics. 1. 10.1504/IJSAMI.2015.069045.

Bottrall, A. F., & World Bank. (1981). Comparative study of the management and organization of irrigation projects (Ser. World bank staff working papers, nr. 458). World Bank.

Clemmens, A. (2006). Improving irrigated agriculture performance through an understanding of the water delivery process. Irrigation and drainage, 55, 223. doi: 10.1002/ird.236

Deltares. Flow1D Technical Reference Manual. SOBEK(3.7.21)

Deltares. Flow1D User Manual. SOBEK(3.7.21)

Dirwai, T. L., Senzanje, A., & Mudhara, M. (2019). Assessing the functional and operational relationships between the water control infrastructure and water governance: a case of tugela ferry irrigation scheme and mooi river irrigation scheme in kwazulu-natal, south africa. Physics and Chemistry of the Earth, 112, 12–20. https://doi.org/10.1016/j.pce.2018.11.002

El Monshid, B. E. F., El Awad O. M. A., Ahmed S. E., 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. Reports and Working Papers. Bonn, German Development Institute.

Elhassan M., Ahmed E., 2008. Watershed degradation and its impacts on agricultural area and crop production in Gezira Scheme. Paper presented at the Nile Basin Development Forum, Friendship Hall Khartoum, Sudan,17-19 November

Elshaikh, A. E. (2018). Developing database system for Irrigation projects. 10.13140/RG.2.2.20479.66723.

Elshaikh, A. E. (2018). Development of a new Software Model to Evaluate and Analyze Irrigation Projects Performance. 10.13140/RG.2.2.18803.27683.

Elshaikh, A. E. (2020). Basics Information the Irrigation system in the Gezira Scheme

Elshaikh, A. E., Shi-hong, Y., Xiyun, J., & Mohammed, M. E. (2018). Impacts of legal and institutional changes on irrigation management performance: a case of the gezira irrigation scheme, sudan. Water, 10(11). https://doi.org/10.3390/w10111579

Ertsen, M. W. (2016). Improvising planned development on the gezira plain, sudan, 1900-1980 (Ser. Palgrave studies in the history of science and technology). Palgrave Macmillan. https://doi.org/10.1007/978-1-137-56818-2

FAO. (2009). Proceedings of the Expert Meeting on How to Feed the World in 2050: 24-26 June 2009, Fao Headquarters, Rome.

Ghumman, A. R., Ahmad, S., Rahman, S., & Khan, Z. (2018). Investigating management of irrigation water in the upstream control system of the upper swat canal. Iranian Journal of Science and Technology. Transactions of Civil Engineering, 42(2), 153–164. https://doi.org/10.1007/s40996-018-0097-0

Ghumman, A. R., Khan, M. Z., & Khan, M. J. (2006). Use of numerical modelling for management of canal irrigation water. Irrigation and Drainage, 55(4), 445–458. https://doi.org/10.1002/ird.265

Ghumman, A. R., Khan, M. Z., Khan, A. H., & Munir, S. (2010). Assessment of operational strategies for logical and optimal use of irrigation water in a downstream control system. Irrigation and Drainage, 59(2), 117–128. https://doi.org/10.1002/ird.464

Gismalla, Y. A. (2009). Sedimentation Problems In The Blue Nile Reservoirs And Gezira Scheme: A Review.

Gismalla, Y. A., & Fadul, E. M. (2011). Design and remodeling of stable canals in central Sudan. Sudan Journal of Agricultural Research (Sudan).

Goelnitz, A., & Al-Saidi, M. (2020). Too big to handle, too important to abandon: reforming sudan's gezira scheme. Agricultural Water Management, 241. https://doi.org/10.1016/j.agwat.2020.106396

Guvele, C. A., & Featherstone, A. M. (2001). Dynamics of irrigation water use in sudan gezira scheme. Water Policy, 3(5), 363–386. https://doi.org/10.1016/S1366-7017(01)00077-0

Hamid, S. H., Mohamed, A. A., & Mohamed, Y. A. (2011). Towards a performance-oriented management for large- scale irrigation systems: case study, rahad scheme, sudan. Irrigation and Drainage, 60(1), 20–34. https://doi.org/10.1002/ird.546

Hashemy Shahdany, S. M., Taghvaeian, S., Maestre, J. M., & Firoozfar, A. R. (2019). Developing a centralized automatic control system to increase flexibility of water delivery within predictable and unpredictable irrigation water demands. Computers and Electronics in Agriculture, 163. https://doi.org/10.1016/j.compag.2019.104862

Heydari, N. (2014). Water productivity in agriculture: challenges in concepts, terms and values. Irrigation and Drainage, 63(1), 22–28. https://doi.org/10.1002/ird.1816

Ibrahim, A. A., Stigter, C. J., Adam, H. S., Adeeb, A. M., & Fadl, O. A. A. (2000). Farmers' practices in On-farm Irrigation Management in the Gezira Scheme, Central Sudan (pp. 20–29). Rural and Environmental Engineering.

JOHNSTONE, H. V. C. The Gezira Irrigation Scheme: Canalization of the Gezira. Minutes of the Proceedings of the Institution of Civil Engineers 1929 227:1929, 68-94

Khan, M. Z., & Ghumman, A. R. (2008). Hydrodynamic modelling for water-saving strategies in irrigation canals. Irrigation and Drainage, 57(4), 400–410. https://doi.org/10.1002/ird.375

Mahgoub, F. (2014). Current Status of Agriculture and Future Challenges in Sudan.

Modernizing irrigation management – the MASSCOTE approach. FAO irrigation and drainage paper. (63). ISSN 0254 – 5284.

Mohamed, A.W. (2010): Assessment of the Role of Agriculture in Sudan Economy.

Mohamed, H. I., Ahmed, E. E., Abbas, O. M., & Mohamed, A. E. (2010). AGRICULTURE AND BIOLOGY JOURNAL OF NORTH AMERICA. Water Allocation and Optimization of Minor Canal Operation. https://doi.org/10.5251/abjna.2010.1.5.1031.1043

Osman, I. S. E. (2015). Impact of improved operation and maintenance on cohesive sediment transport in gezira scheme, sudan (dissertation). CRC Press/Balkema.

Osman, I. S. E., Mohammed A., Awad K., Hozaifa A., Maab I., Amal. (2020). A Mathematical model using different design approaches for better sediment AND Water management in irrigation Canals

Osman, I. S. E., Schultz, B., Suryadi, F. X., Mohamed, Y., & Osman, A. K. (2011). Improving the operation and maintenance for better sediment and water management in Gezira Scheme, Sudan. In Proceedings of the ICID 21st International Congress on Irrigation and Drainage, Tehran, Iran, 15-23 October, 2011 (pp. 51-62). ICID.

Plusquellec Hervé L. (1990). The Gezira irrigation scheme in Sudan : objectives, design, and performance (Ser. World bank technical paper, no. 120). World Bank.

Seibert, S., Henrich, V., Frenken, K., Burke, J., 2013. Update of the Digital Global Map of Irrigation Areas to Version 5. FAO Land and Water Division, Rome, Italy (Accessed 20 November 2019). http://www.fao.org/3/I9261EN/i9261en.pdf.

Seleshi, A., Matthew, M., Tammo, S., Abdalla, A. (2008). A Review of Hydrology, Sediment and Water Resource Use in the Blue Nile Basin.

Smit, H. (2019). Making water security: A morphological account of Nile River development. CRC Press / Balkema - Taylor & Francis Group.

The Gezira Irrigation Act of 2005.

Tyagi, A. C. (2017). Role of irrigation for sustainable food production: outcomes of second world irrigation forum. Irrigation and Drainage, 66(2), 289–290. https://doi.org/10.1002/ird.2134

Umolu, E. C. (2015). Linking institutional and policy changes to agricultural productivity: [a case study of the gezira irrigation scheme, sudan] (dissertation). UNESCO-IHE.

Wallach, B. (1988). Irrigation in sudan since independence. Geographical Review, 78(4), 417–434.

Wegerich, K., & Hussain, A. (2016). Creating accountability: representation and responsiveness of the irrigation bureaucracy in punjab, pakistan. Water International, 41(5), 662–681. https://doi.org/10.1080/02508060.2016.1185890

Woldegebriel, E. (2011). Irrigation management transfer in the gezira scheme, sudan : a case study on farmers' operation and maintenance strategies in tuweir minor canal. s.n. http://edepot.wur.nl/167523.

Appendix

Appendix A. Hydraulic Structures

Sluice gates

Figure 71. Sluice Gate Regulator

Moveable weirs:

Figure 72. Night Storage Weirs

Figure 73. Moveable Weir

Figure 74. Field Outlet Pipes

Figure 75. pumping from the Main Gezira Canal

Appendix B. Equations and definitions

The equation of Penman (1948) that is used by Farbrother in Sudan is:

$$E_0 = \mathit{\Delta}\, R_n + \gamma\, (e_a - e_d)\, f(u)\, \mathit{\Delta} + \gamma$$

Where:

E_0	Penman evaporation (mm per day) from open water
$\mathit{\Delta}$	Slope of the saturation vapor pressure (kPa °C^{-1})
R_n	Net solar radiation (mm per day)
γ	Psychometric constant (kPa °C^{-1})
e_a	Saturation vapor pressure at mean temperature (kPa)
e_d	Mean actual vapor pressure (kPa)
$f(u)$	Wind function suggested by Penman (1956)
u	Wind speed (m s−1) at 2 m height

From the above equation and using the local conditions, Farbrother manages to produce the crop factors presented in figure 9.

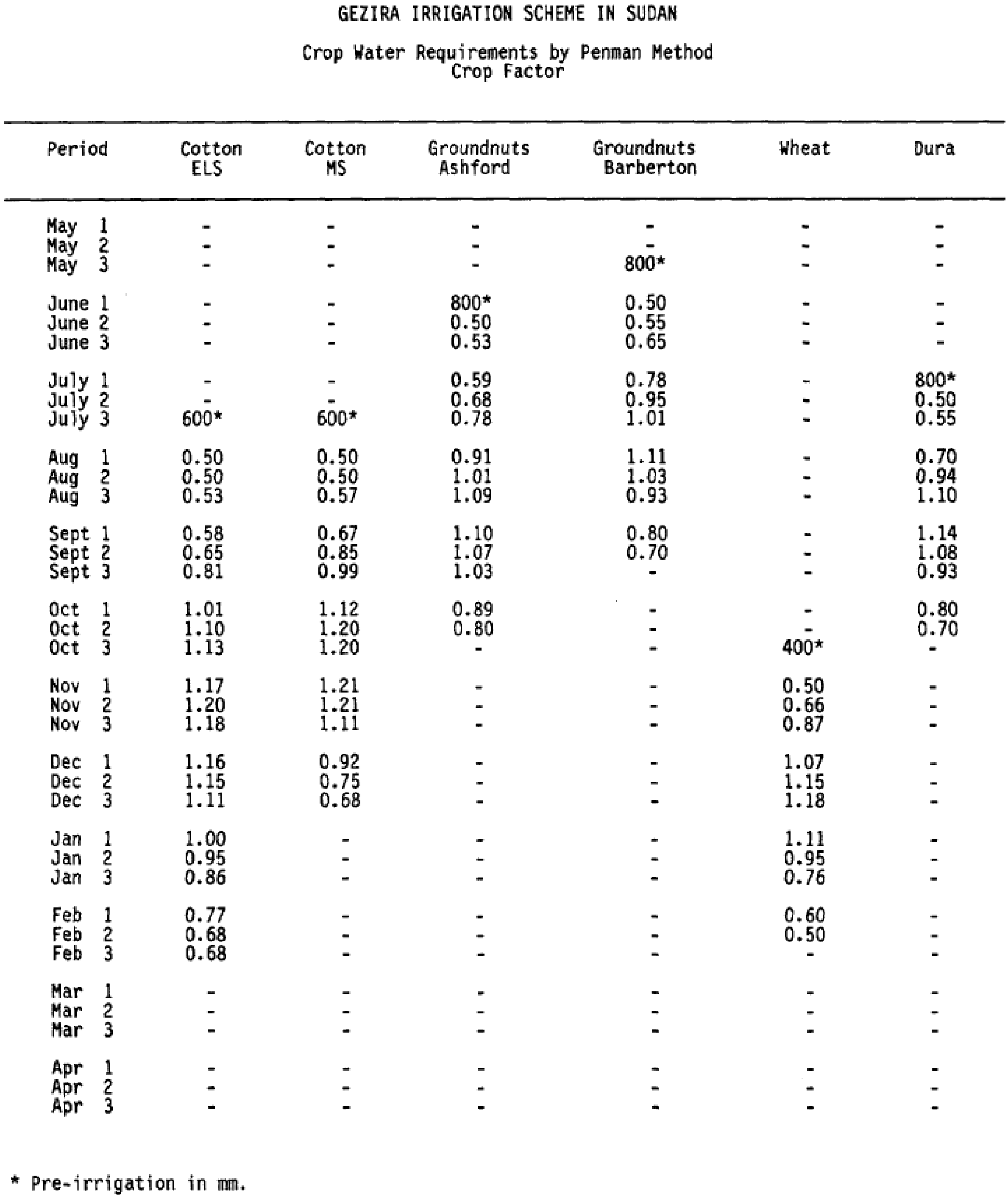
Definitions

- Moisture Availability Index (MAI) is the ratio of the dependable precipitation (DP) to ETc where DP is the precipitation at a 75% probability level of occurrence.

- Irrigation efficiency (E) is a dimensionless ration between water used to the total amount of water applied. It includes several types like conveyance, application, distribution and overall efficiencies.

- Water Use Efficiency (WUE) is the of crop production to evapotranspiration of the crop.

- Water Productivity (WP) is the ratio of crop yield (out) to amount of water applied (input), in includes several types of productivity, like land productivity, economical productivity,



GEZIRA IRRIGATION SCHEME IN SUDAN

Crop Water Requirements by Penman Method
Crop Factor

Period	Cotton ELS	Cotton MS	Groundnuts Ashford	Groundnuts Barberton	Wheat	Dura
May 1	-	-	-	-	-	-
May 2	-	-	-	-	-	-
May 3	-	-	-	800*	-	-
June 1	-	-	800*	0.50	-	-
June 2	-	-	0.50	0.55	-	-
June 3	-	-	0.53	0.65	-	-
July 1	-	-	0.59	0.78	-	800*
July 2	-	-	0.68	0.95	-	0.50
July 3	600*	600*	0.78	1.01	-	0.55
Aug 1	0.50	0.50	0.91	1.11	-	0.70
Aug 2	0.50	0.50	1.01	1.03	-	0.94
Aug 3	0.53	0.57	1.09	0.93	-	1.10
Sept 1	0.58	0.67	1.10	0.80	-	1.14
Sept 2	0.65	0.85	1.07	0.70	-	1.08
Sept 3	0.81	0.99	1.03	-	-	0.93
Oct 1	1.01	1.12	0.89	-	-	0.80
Oct 2	1.10	1.20	0.80	-	-	0.70
Oct 3	1.13	1.20	-	-	400*	-
Nov 1	1.17	1.21	-	-	0.50	-
Nov 2	1.20	1.21	-	-	0.66	-
Nov 3	1.18	1.11	-	-	0.87	-
Dec 1	1.16	0.92	-	-	1.07	-
Dec 2	1.15	0.75	-	-	1.15	-
Dec 3	1.11	0.68	-	-	1.18	-
Jan 1	1.00	-	-	-	1.11	-
Jan 2	0.95	-	-	-	0.95	-
Jan 3	0.86	-	-	-	0.76	-
Feb 1	0.77	-	-	-	0.60	-
Feb 2	0.68	-	-	-	0.50	-
Feb 3	0.68	-	-	-	-	-
Mar 1	-	-	-	-	-	-
Mar 2	-	-	-	-	-	-
Mar 3	-	-	-	-	-	-
Apr 1	-	-	-	-	-	-
Apr 2	-	-	-	-	-	-
Apr 3	-	-	-	-	-	-

* Pre-irrigation in mm.

Figure 76. Crops factors generated by Farbrother (Plusquellec, 1990)

Appendix C. Tables and Figures

Table 17. Irrigation scheduling in Toman Minor canal in September 2012 (Osman, 2015)

Day	1st reach					2nd reach					3rd reach					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1			op		op				op				op		op	op
2			op				op								op	op
3			op				op				op		op			op
4	op		op				op				op		op			op
5	op						op				op					op
6																
7																
8	not recorded															
9	op		op				op		op		op		op			op
10	op		op		op		op	op	op		op		op			op
11	op				op			op	op		op		op			op
12			op		op			op	op				op			op
13			op						op		op					op
14									op							op
15	not recorded															
16			op					op					op			op
17	op		op						op							op
18	op						op									op
19	op		op								op					
20	op		op		op				op		op		op			
21	not recorded															
22	op		op					op	op				op			op
23	op		op					op			op		op			
24	op		op		op				op		op		op			
25	op		op		op			op					op			
26	op		op				op				op					op
27	op		op		op			op					op			
28	not recorded															
29	op		op		op		op		op		op					op
30	op		op		op			op	op							op

Table 18. Discharge (m3/s) for canal and crest level (CL) (m+MSL) for the control structures at 9.1 and 12.5 km from the offtake during summer season of 2012

Day	Zananda	Gimillia	G/ Elhosh	Bellola	W/ Elmahi	A/Gomri	Gemoia	Toman	CL 9.1	CL 12.5
July										
1	3.51									
2	3.51						0.42	0.26		
3	3.51	0.43	0.22	0.33	0.39		0.43	0.29		
4	3.51	0.40	0.38	0.37	0.49	0.15	0.49	0.68	411.55	410.43
5	3.51	0.40	0.37	0.38	0.53	0.05	0.46	0.51	411.73	410.43
6	3.51	0.37	0.30	0.36	0.43	0.03	0.46	0.47	411.73	410.43
7	3.51	0.33	0.22	0.33	0.34	0.01	0.45	0.42	411.73	410.43
8	3.51	0.34	0.24	0.33	0.43	0.23	0.49	0.42	411.73	410.43
9	4.36	0.16	0.47	0.33	0.50	0.26	0.58	0.20	411.73	410.43
10	4.36	0.17	0.37	0.40	0.50	0.06	0.61	0.28	411.73	410.43
11	4.36	0.16	0.25	0.35	0.43	0.00	0.52	0.34	411.65	410.43
12	4.36	0.15	0.32	0.31	0.64	0.00	0.56	0.10	411.55	410.43
13	4.19	0.14	0.30	0.22	0.35	0.00	0.38	0.09	411.55	410.43
14	4.19	0.12	0.27	0.13	0.05	0.00	0.20	0.07	411.55	410.43
15	5.17	0.28	0.40	0.13	0.05	0.00	0.20	0.07	411.55	410.43
16	4.03	0.28	0.40	0.15	0.06	0.02	0.20	0.07	411.55	410.43
17	3.88	0.28	0.40	0.14	0.06	0.05	0.24	0.10	411.55	410.43
18	3.88	0.17	0.33	0.22	0.05	0.05	0.20	0.07	411.55	410.43
19	4.07	0.17	0.30	0.17	0.05	0.02	0.16	0.07	411.58	410.43
20	4.07	0.15	0.29	0.17	0.05	0.02	0.16	0.09	411.58	410.43
21	3.35	0.12	0.28	0.17	0.05	0.02	0.16	0.10	411.58	410.43
22	2.31	0.12	0.30	0.19	0.05	0.03	0.20	0.12	411.58	410.43
23	2.10	0.04	0.21	0.13	0.00	0.00	0.05	0.02	411.58	410.43
24	2.12	0.00	0.16	0.00	0.00	0.00	0.07	0.04	411.58	410.43
25	2.66	0.00	0.06	0.00	0.00	0.00	0.00	0.02	411.58	410.43

Day	Zananda	Gimillia	G/ Elhosh	Bellola	W/ Elmahi	A/Gomri	Gemoia	Toman	CL 9.1	CL 12.5
July										
26	2.66	0.00	0.00	0.00	0.00	0.00	0.00	0.01	411.58	410.43
27	1.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	411.58	410.43
28	1.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	411.58	410.43
29	1.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	411.58	410.43
30	0.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	411.58	410.43
31	0.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	411.58	410.90
August										
1	0.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	411.75	410.80
2	0.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	411.75	410.80
3	0.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	411.75	410.85
4	0.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	411.75	410.85
5	0.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	411.65	410.85
6	0.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	411.65	410.90
7	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	411.65	410.88
8	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	411.65	410.80
9	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	411.65	410.88
10	1.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	411.65	410.75
11	1.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	411.75	410.57
24	0.97	0.00	0.00	0.00	0.00	0.00	0.00	0.00	411.70	410.85
25	2.52	0.08	0.00	0.08	0.05	0.00	0.07	0.01	411.70	410.85
26	2.52	0.28	0.07	0.09	0.28	0.00	0.20	0.14	411.70	410.85
27	2.52	0.28	0.08	0.09	0.28	0.00	0.20	0.12	411.70	410.85
28	2.13	0.04	0.06	0.05	0.15	0.00	0.16	0.04	411.70	410.65
29	2.13	0.14	0.16	0.31	0.28	0.17	0.38	0.08	411.67	410.65
30	2.13	0.00	0.00	0.09	0.00	0.00	0.61	0.03	411.67	410.65
31	1.78	0.11	0.06	0.12	0.11	0.06	0.43	0.11	411.70	410.65

Day	Zananda	Gimillia	G/ Elhosh	Bellola	W/ Elmahi	A/Gomri	Gemoia	Toman	CL 9.1	CL 12.5
Sept.										
1	2.96	0.22	0.11	0.15	0.21	0.11	0.24	0.20	411.70	410.65
2	5.94	0.37	0.13	0.15	0.21	0.15	0.24	0.23	411.70	410.65
3	4.10	0.28	0.13	0.33	0.21	0.15	0.24	0.30	411.52	410.40
4	7.20	0.48	0.18	0.24	0.28	0.06	0.61	0.28	411.70	410.40
5	3.85	0.34	0.16	0.24	0.15	0.00	0.65	0.10	411.70	410.40
6	3.85	0.34	0.27	0.14	0.28	0.03	0.66	0.18	411.70	410.40
7	3.85	0.28	0.28	0.19	0.15	0.04	0.57	0.25	411.70	410.40
8	2.94	0.21	0.29	0.24	0.02	0.06	0.48	0.31	411.70	410.40
9	2.94	0.21	0.27	0.24	0.26	0.24	0.45	0.40	411.70	410.40
10	2.94	0.21	0.25	0.22	0.25	0.06	0.56	0.54	411.70	410.40
11	3.57	0.33	0.30	0.40	0.52	0.06	0.58	0.59	411.70	410.40
12	3.57	0.29	0.19	0.31	0.52	0.06	0.56	0.35	411.70	410.40
13	3.57	0.30	0.19	0.31	0.52	0.06	0.47	0.36	411.70	410.40
14	3.57	0.21	0.16	0.30	0.52	0.25	0.47	0.41	411.70	410.40
15	3.57	0.29	0.13	0.30	0.52	0.44	0.47	0.47	411.70	410.40
16	3.57	0.38	0.15	0.39	0.52	0.44	0.59	0.47	411.70	410.40
17	3.57	0.49	0.19	0.39	0.52	0.44	0.58	0.54	411.70	410.40
18	3.57	0.35	0.13	0.31	0.64	0.35	0.56	0.63	411.70	410.40
19	3.85	0.32	0.12	0.28	0.53	0.35	0.54	0.63	411.70	410.40
20	3.85	0.30	0.12	0.27	0.53	0.41	0.56	0.76	411.70	410.40
21	3.71	0.32	0.16	0.31	0.53	0.37	0.56	0.65	411.70	410.40
22	3.57	0.33	0.21	0.35	0.52	0.32	0.56	0.55	411.70	410.40
23	3.57	0.33	0.21	0.35	0.52	0.40	0.61	0.39	411.70	410.75
24	3.57	0.33	0.21	0.35	0.52	0.40	0.61	0.39	411.70	410.75
25	3.57	0.33	0.21	0.35	0.52	0.26	0.47	0.58	411.70	410.75
26	3.57	0.29	0.17	0.35	0.52	0.44	0.45	0.42	411.70	410.45
27	3.57	0.27	0.17	0.33	0.52	0.00	0.42	0.42	411.70	410.52

Day	Zananda	Gimillia	G/ Elhosh	Bellola	W/ Elmahi	A/Gomri	Gemoia	Toman	CL 9.1	CL 12.5
Sept.										
	3.57	0.38	0.19	0.35	0.52	0.00	0.45	0.44	411.70	410.52
29	3.57	0.49	0.22	0.38	0.52	0.00	0.47	0.47	411.70	410.52
30	3.57	0.46	0.22	0.38	0.52	0.00	0.47	0.47	411.70	410.52
October										
1	3.57	0.46	0.22	0.38	0.52	0.00	0.56	0.50	411.70	410.52
2	4.10	0.28	0.18	0.33	0.52	0.00	0.42	0.29	411.70	410.52
3	4.10	0.36	0.21	0.38	0.52	0.00	0.56	0.58	411.70	410.52
4	4.10	0.87	0.20	0.50	0.52	0.00	0.61	0.58	411.70	410.40
5	4.10	0.88	0.22	0.53	0.52	0.00	0.63	0.58	411.70	410.40
6	4.10	0.90	0.23	0.56	0.52	0.00	0.66	0.58	411.70	410.40
7	3.85	0.93	0.28	0.59	0.52	0.00	0.71	0.58	411.70	410.40
8	3.85	0.84	0.25	0.50	0.52	0.00	0.71	0.58	411.70	410.40
9	3.85	0.79	0.23	0.13	0.52	0.00	0.71	0.61	411.70	410.40
10	3.85	0.12	0.37	0.13	0.00	0.00	0.66	0.58	411.35	410.40
11	5.40	0.12	0.37	0.13	0.00	0.00	0.66	0.35	411.35	410.40
12	2.97	0.12	0.37	0.13	0.00	0.00	0.66	0.35	411.35	410.40
13	2.97	0.12	0.37	0.13	0.00	0.00	0.66	0.35	411.35	410.40
14	2.64	0.12	0.37	0.00	0.00	0.00	0.69	0.43	411.35	410.40
15	2.64	0.00	0.00	0.00	0.00	0.00	0.69	0.43	411.68	410.40
16	3.45	0.19	0.00	0.00	0.34	0.00	0.63	0.43	411.68	410.40