Journal of Agricultural Science and Engineering
Vol. 7, No. 2, 2021, pp. 23-29
http://www.aiscience.org/journal/jase
ISSN: 2381-6821 (Print); ISSN: 2381-6848 (Online)

Development of Surface Spate Irrigation System Capable to Irrigate a Large-Scale Area at the Lowest Cost

Hassan Elhaj Hamed Alsayim[1, *], Aboubaker Ahmed Osman[2], Salah Ahmed Ali[2]

[1]Department of Agricultural Engineering, Faculty of Agriculture, Nile Valley University, Darmali, Sudan
[2]Department of Civil Engineering, Faculty of Engineering & Technology, Nile Valley University, Atbara, Sudan

Abstract

Irrigated area in River Nile state faces many difficulties. The most difficult is the need of large quantity of energy to operate. Surface irrigation is the least energy consuming irrigation scheme but it requires a high cost infra-structure (dams and storage facilities). Atbara River has natural steeply slope, in some places more than 75 cm/km. This steeply slope made it perfect for developing irrigation system, a mix of spate and surface irrigation. The developed irrigation system is expected to be less expensive than surface irrigation and more effective than spate irrigation. This paper aims to investigate the possibility of irrigating 630,000 hectares on the left bank of Atbara River using surface spate irrigation system. The hydrology of the Atbara River was studied and suitable cropping pattern were chosen accordingly. The terrain analysis was carried out for planning the irrigation and drainage canals with minimum construction cost. The total area was divided into three sub zones according to the topography surveys of the area. Software programs were used and Excel templates were created to vacillate the interdependent design parameters. Five types of soil were identified and mapped are: sand dune; thin wavy layer of sand over a flat clay soils; flat desert lands; cracked dark-colored clay soils and the "vertesol" lowlands. The arable land was estimated to be 445,200 hectares represent 70% of the total area. The maximum water requirement of the crops ranged from 6.75 to 8.98 mm/day. The total discharge for the three main canals is about 607 m^3/s. The required discharge to meet the maximum needs was estimated at 1012 million m^3/month (33.7 million m^3/day) with an average of 14 working hours per day and the total discharge required is about 670 m^3/s (increased by 10% as transfer losses). The irrigation canal system was designed, the total length of the canals is 3,426 km and the total irrigated areas is 419,605 hectares. The total volume of the excavation and filling (transferred) works is about 34,686,189 m^3 and 121,983,197 m^3, respectively. The paper concluded that more than 90% of the suitable agricultural area can be irrigated using surface spate irrigation system with lowest energy consumption.

Keywords

Surface, Spate Irrigation, Atbara River Hydrology, Tekzi Dam, Planning, Canals Design

Received: April 30, 2021 / Accepted: May 31, 2021 / Published online: June 28, 2021

1. Introduction

The world's population is expected to increase from 7.7 billion to reach 9.7 billion in 2050 [1]. Therefore, it is necessary to increase food production. In many areas around the world, 70% of usable water is used in the agricultural sector. By the year 2050, providing food for more than nine billion people, requires an increase in agricultural production equivalent to 50% of the current production, and 15% increase in the water consumed [2].

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* Corresponding author
E-mail address: alsayim101@yahoo.com (H. E. H. Alsayim)

Sudan is considered to be rich with abundant natural recourses represented in vast area of agricultural land, various climates due to its wide geographical extension and abundant water resources. Fertile agricultural lands extend throughout the country from light sandy loams in the west to clay plains in the center and east. Water resources varied including rains, ground water, the Nile, its tributaries and other rivers. Sudan has an area of 188 million hectares, of which about 84 million hectares (44%) are arable. Sudan's economy is highly dependent on agriculture, which takes in an estimated 43 percent of its labour force according to estimates by the International Labor Organization, and accounts for about 30 percent of its GDP [3].

Crop production in Sudan is diversified and includes cereal crops (maize, millet, sorghum, and wheat); oilseeds (peanuts, sesame, sunflower); cash crops (cotton and sugar cane); forage crops (alfalfa, sorghum and Rhodes grass); and legumes (beans and peas) in addition to horticultural crops. Although there is a significant potential for agricultural development in Sudan, the agricultural area faces a number of challenges that have constrained and restricted prospects for sustainable growth to support the economy that depend on the sector for their livelihoods [4].

In 2020, the economic crisis, which was exacerbated by a set of complex and intersecting factors, including the COVID-19 pandemic and climate change, led to a deterioration in the nutrition situation and food security in Sudan [5].

The Integrated Food Security Phase Classification (IPC) for June to September 2020 estimated that 9.6 million people in Sudan facing a crisis or worse levels of food insecurity of whom more than 2.2 million are in an emergency situation. Additionally, it is estimated that approximately 15.9 million people are under stress and these numbers indicate that most people are transitioning to worse stages of food insecurity [5].

River Nile State is located within the desert and semi-desert ranges, and therefore its climate is characterized by low rainfall (0-100 mm) with a relatively short season between July and September with a marked fluctuation in the amount of rain and its timing. The State is characterized by dry summer months with daytime temperatures rising to more than 43°C, and mild winter months with temperatures dropping to below 16°C. Wind speeds are high most of the time (8-12.8 Km/hour). Due to wind speed and low relative humidity, the state is characterized by a very high evaporation rate ranging between 1677 and 2336 mm per year, however, due to the topography of the flat land and the presence of the Nile and Atbara River, the expansion of irrigated agriculture is promising [4].

The arable land in the state is about 4 million hectares (about 32% of the state's area) and has the largest source of water (Nile River and Atbara River) in addition to many seasonal valleys and an underground water reservoir that extends across half of the state's area. In spite of that, the cultivated of these lands does not exceed 1% of the area. Perhaps one of the most important reasons impeding the expansion of agricultural land reclamation is the cost of pumping water vertically and horizontally, as the surface sources are sometimes hundreds of kilometers away from agricultural lands, and often the land rises from the vertical source to about 50 meters. The establishment of large installations of dams and reservoirs faced many problems such as the dispersal of lands in separate areas, the high rise of agricultural lands compared to water sources, in addition to the high construction cost of such projects [4].

A well-designed and maintained irrigation system will keep the environmental impacts, as well as the construction and operating costs of irrigation as low cost as possible. The water and energy consumption required to distribute the water can be reduced through proper planning and optimal management of the irrigation system. In addition, installing high-efficiency pumping equipment, or making improvements to an existing pumping station, will help reduce unnecessary pumping losses [6].

In 1994, a flood irrigation system was introduced in the Nile River State, where a connection canal was opened from the Atbara River to irrigate about 12,600 hectares by flood (spate) irrigation on the right bank of the river. The experiment based on the existence of an estimated difference in the slope of the canal is 5 cm/km compared to the course of the Atbara River of 75 cm/km, which can connect water to the lands bordering the river with a height of more than 0.6 meters from the water level in the river for every kilometer of the connecting canal along the river. The experiment was successful, as the results were concluded for the ability to deliver water to more than 42,000 hectares cultivated with grains, in addition, this method led to reduce energy cost as it does not require any pumping cost. The experiment was not destined to continue due to the short flood season and the seasonality of river runoff, and the flood period coincides with the season of cultivating crops with weak economic returns, in addition to the fact that the agricultural land holdings adjacent to the river have many obstacles to the continuation of the experiment [4].

Irrigation represents a large part of energy consumption in the agricultural sector. The relationship between water and energy is increasingly becoming a concern for researchers, operators and users of irrigation [7], [8]. It is estimated that global demand for energy will increase by 30% by 2040, which requires an increase in global energy production [9]. While, water demand is expected to increase by about 55% by 2050, with the increasing severity and scarcity of water on a large scale due to climate change [10]. This paper aims to design a surface spate irrigation system capable to irrigate a large-scale area at the lowest cost without the need for large hydraulic installations such as dams and pump stations.

2. Materials and Methods

The study was carried out in 2011 in River Nile state, Sudan in an area of about 630,000 hectares on the left bank of the Atbara River (Figure 1). The study area is located between 1786980-1889000 m North and 630180-701350 m East of zone 36 Q.

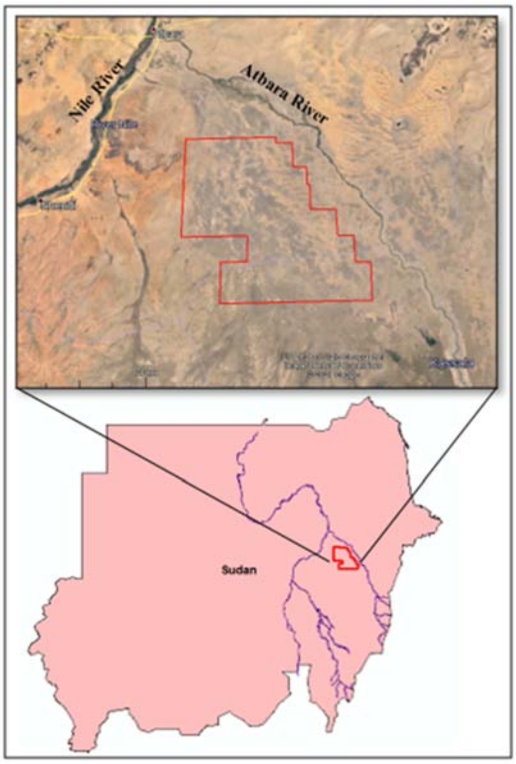

Figure 1. Spatial image of study area.

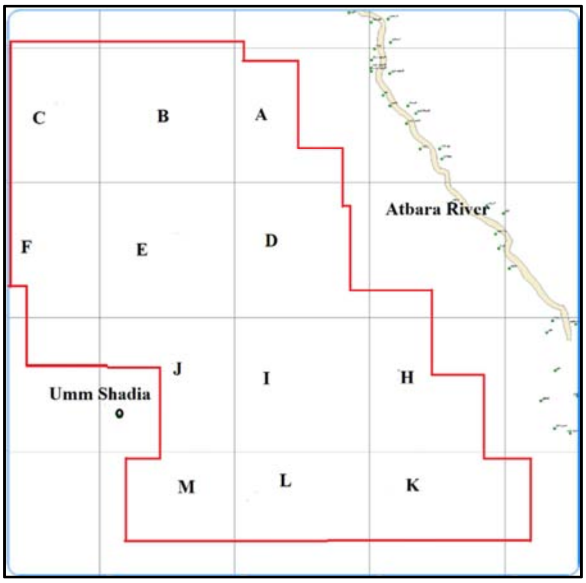

Figure 2. Twelve quadratic working zones identified from A-L.

Topographic surveys were prepared for the study area. The study area was divided into 12 quadratic working zones identified from A-L. Each quadratic working zone is 25 × 25 km^2 distributed between the Atbara River and Umm Shadia village (Figure 2). Four of these quadratic working zones cannot be studied, A, D, H, and K which identified as un accessible sand dunes, represent 33% of the total area.

Satellite images with laboratory soil sampling were analyzed to characterize the soil. Soil samples were collected from random points, so that each point represents a part of the study area estimated at 25 × 25 km^2, taken from two depths 0-30 cm and 30-90 cm. Soil samples were analyzed to determine soil physical and chemical properties. The coordinates of each point were determined by the GPS device for soil digital mapping.

The soil was analyzed to find the proportions of sand and clay using sieves and the degree of saturation was determined, salinity, the soil reaction, soil bulk density, the sodium and potassium elements and a calibration was performed to determine the proportions of carbonate, calcium and magnesium. The nitrogen level, the cation exchange capacity, the amount of dissolved potassium and available phosphorous were also measured.

The CLIMWAT 2.0 program was used to identify climate parameters collected from six adjacent metrological stations surrounding the studied area, namely: Atbara, Hudeiba, Shendi, New Halfa, Aroma and Derudeb. The climate parameters include: rainfall data, mean maximum and mean minimum temperatures, mean relative humidity, mean sunshine, wind speed at 2 m height and evapotranspiration. ArcMap 9.3 GIS program was used to process the above parameters and mapping climate data.

Food and Agriculture Organization (FAO) CropWat program was used to estimate the crop water requirements using the Penman Mountain formula [11]:

$$\mathrm{ET}_o = \frac{0.408(\mathrm{Rn}-\mathrm{G}) + \gamma \frac{900}{\mathrm{T}+273}\mathrm{u}_2(\mathrm{es}-\mathrm{ea})}{\Delta + \gamma(1+0.34\mathrm{u}_2)}$$

Where: ETo = reference crop evapotranspiration (mm/day), Δ = slope of the saturated vapor pressure curve and air temperature (kPa/°C), Rn = net radiation flux (MJ. M^2/day), G = sensible heat flux into the soil (MJ. M^2/day), γ = moisture constant (kPa/°C), T = mean air temperature (°C), u2 = wind speed at 2 m above the ground (m/s), es = saturated vapor pressure (kPa), ea = actual vapor pressure (kPa), es - ea = saturated vapor pressure deficit (kPa).

For the suggested crops (Sesame, Groundnut, Sun flower, Bean, Sorghum and Wheat) the total periods, growth stages and planted dates; regional research recommendations were used. Crops coefficient, critical depilation, maximum rooting depths and yield response factors; FAO recommendations were considered [11]. The CropWat program was used to design and management the irrigation scheme. The crop water requirements for each crop were calculated using the equation [11]:

$$\mathrm{ETcrop} = \mathrm{Kc} \times \mathrm{ETo}$$

Where: ETcrop = crop water requirement, Kc = Crop coefficient

The total irrigation requirements were calculated and compared to the expected monthly yield from Atbara River after the construction of Takzi dam (Figure 3). Takzi dam total storage is 14 milliard cubic meters. The filling period of its lake has finished in flooding season of 2010 [4].

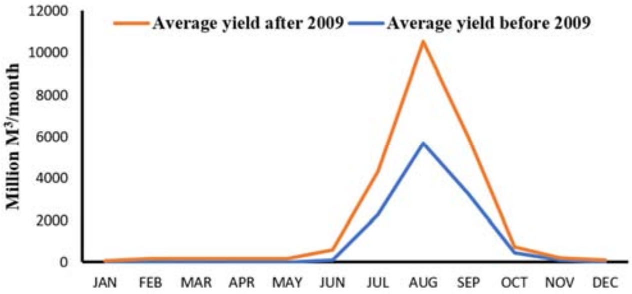

Figure 3. Atbara river monthly yield.

Minor canals are designed with 5 kilometers in length and 1.5 kilometers apart. Minors are designed with 3 meters bed width, while canal slopes are ranged between 10 – 30 cm/kilometer to give the minimum earth works. Water heights are calculated by try and error according to Manning's formula. The minor depth was designed for discharge of 1.19 m^3/s then the designed depth ranged between - 0.66 meters and + 0.88 meters.

The canal inner, outer side slope and free boards are taken 2, 3 and 0.3 m respectively. The banks of the minor canals are assumed to be well compact and hence the hydraulic gradient line through the banks is assumed to be 6: 1. The minimum command height of water over adjacent ground levels to perform gravity irrigation is assumed to be 0.5 m.

The irrigation block size is assumed to be 5×1.5 kilometers with field distributed canals locally known as Abu XX and Abu VI (Figure 4). The unit of irrigation (locally known as Hawasha) is in area (2.1 hectares) with dimension of 280×75 m^2.

For each canal the recommended water levels are calculated according to prescribed command height and then an assumed surface water was calculated according to canal slope, then this surface level was raised by the maximum negative difference between assumed and recommended water level. The whole calculations were repeated for different slopes to give the minimum earth work and the canal section was redesigned with the new slope.

The construct of each canal is processed by compact road area of design width along the length of the reach of the canal to design height of CL (cut level) and then a trapezoidal shape is cut to the required bed level in what is called reshape process. The calculation of excavation and filling was done by equating the quantities transported from the strip, the cut quantities and the quantities recovered from the soil (Figure 5).

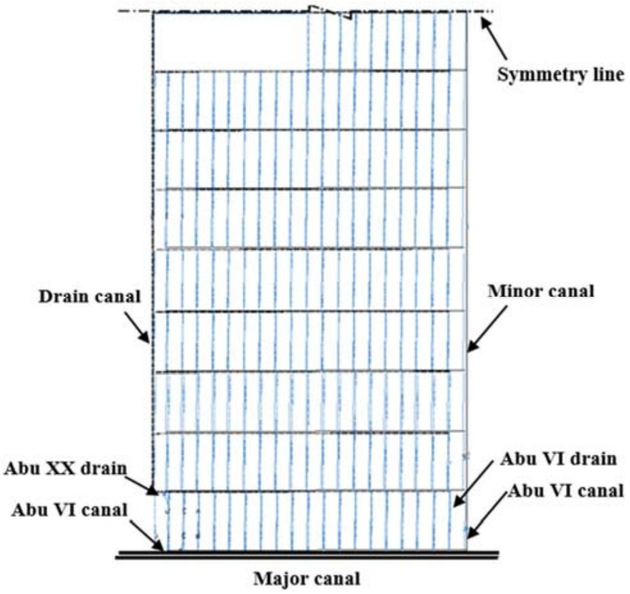

Figure 4. Typical irrigation block.

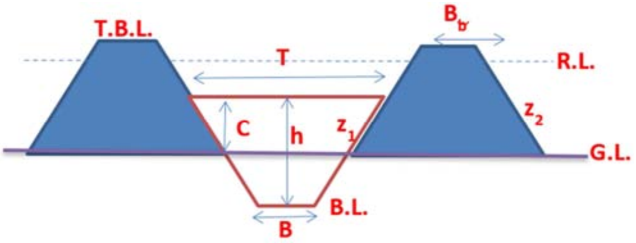

Figure 5. Typical canal cross section.

T.B.L. = Top bank level, T = Free width, W.L. = Water level, C = Command, h = Water height, z_1 = Inner slope, z_2 = Outer slope, R.L. = Reshape level, G.L. = Ground level, B.L. = Bed level.

To design the cross-section of the canal, the Manning equation was used [12]:

$$Q = \frac{A}{n} R^{\left(\frac{2}{3}\right)} \sqrt{S}$$

Where: Q = canal drainage, A = canal cross-sectional area, n = Manning coefficient, R = hydraulic radius, S = canal longitudinal slope.

Then the water level was calculated as follows:

$$\mathrm{WL_r} = \mathrm{G.L} + \mathrm{C}$$

And the water level at x distance from the beginning of the canal calculated as follows:

$$WL_x = WL_o + x * S$$

Where WL_r, WL_x, WL_0 is the water level at the beginning of the canal, at the distance x and the required water level, respectively; G. L is ground surface level; C is the height of the required water level above the ground surface and S is the slope of the canal.

Excel templets were created to vacillate the interdependent design parameters.

3. Results and Discussion

3.1. Soil Properties

According to the analysis and classification of the soil, the study area is a desert land covered with a thin layer of soil that contains gravel. The modern formation includes sand dune west of the River and floodplain sediments of the Atbara River Basin. The differences in the chemical properties of the soil between the south and the north of the study area are due to different rainfall and runoff rates. Five types of soil were identified and mapped in the study are: The first type is sand dune, which is a soil that is dirt-colored loam sand, this type of soil have low salinity and soda due to high content of sand, yet it is poor soil and need special types of irrigation methods. The second type contains thin wavy layer of sand over a flat clay soils with little gravel and high content of calcium carbonate, the area of this type tends toward the northwest. The third type described as flat desert lands and has a high content of cracked clay known as montmorillonite, which is of medium salinity and contains carbonate grain. The fourth type represents cracked, dark-colored clay soils containing a high percentage of the clay mineral (montmorillonite); this type is located in the watercourses (Valleys). The fifth type is described as the "vertesol" lowlands in which the flow is accumulated and locally called (Mayea).

The arable land was estimated to be 419,605 hectares represent 70% of the total area. All lands (except sand dunes) were classified as the second and third class according to the Soil Taxonomy, USDA Soil Survey Staff [13], what is known as medium and low validity for agricultural use.

Table 1. Crops water requirement.

Crop/Month	Decade	Sesame	Groundnut	Sun flower	Bean	Sorghum	Wheat
June	1					2.75	
	2		3.79			2.84	
	3		3.69			3.66	
July	1	3.12	4.03	3.12		5.11	
	2	3.04	5.98	3.04		6.5	
	3	4.15	7.89	3.27		7.74	
August	1	6.00	8.98	4.83		7.88	
	2	7.53	8.55	6.3		7.45	
	3	8.26	8.55	8.11		7.48	
September	1	8.36	7.71	8.78		6.76	
	2	8.38	6.55	8.81		5.65	
	3	8.07	5.23	8.58		4.52	
October	1	5.64	4.42	8.35			
	2	2.79		7.49			
	3			4.97	3.36		
November	1			2.88	3.24		
	2				4.00		1.85
	3				5.26		1.8
December	1				6.45		1.76
	2				6.75		2.07
	3				6.68		3.73
January	1				6.53		5.38
	2				5.53		6.46
	3				2.94		6.97
February	1						7.47
	2						7.89
	3						7.85
March	1						6.36
	2						4.37
	3						2.78

3.2. Irrigation Requirement

The CRPWAT program was used to estimate the water requirements of proposed crops show at Table 1. The study found that the maximum value of evapotranspiration of the reference crop was 9.83 mm/day, recorded in June, while the lowest value is 5.53 mm/day, recorded in January. The maximum water requirement of the crop ranged from 6.75 to 8.98 mm/day. These results are consistent with result obtained by Alsayim [14], which estimated the evapotranspiration rate in the Atbara region at 6.26 mm/day in December. Thus, the irrigation requirements are estimated at 1012 million m^3/month. The required discharge to meet the maximum needs was estimated at 33.7 million m^3/day (80.5 m^3/ha/day) with an average of 14 working hours per day and the total discharge required is about 670 m^3/s (0.0016 m^3/ha/s).

3.3. Irrigation Network Planning

According to the Topographic survey maps and comparative with satellite images and remote sensing data. It was observed that there is a large variation between three zones of the study area. The southern zone is more difficult for irrigation than the northern and middle zones. As a result of this variation, three separated irrigation networks are planned (Figure 6).

3.4. Irrigatin and Drain System Design

The canals are designed to meet the irrigation requirements with lowest cost and high efficiency. The study area was divided into three zones; each zone was irrigated by separated main canal namely; main canal 1, main canal 2 and main canal 3. Each main canal feeds 5 to 9 majors which are fed between 17 to 36 minors. Each minor irrigates about 840 hectares (termed as block). The total discharge for the three main canals is about 607.1 m^3/s. Figure 6 show the zone 1, zone 2 and zone 3 network canals layout.

Atbara River is a permanent river with a discharge of 11,200 Mm^3/year, measured in Atbara. The slope of the river is 0.5 m/km, which allows flood irrigation without pumping, as in Adrama project [4], this type of irrigation can be applicable in the study area.

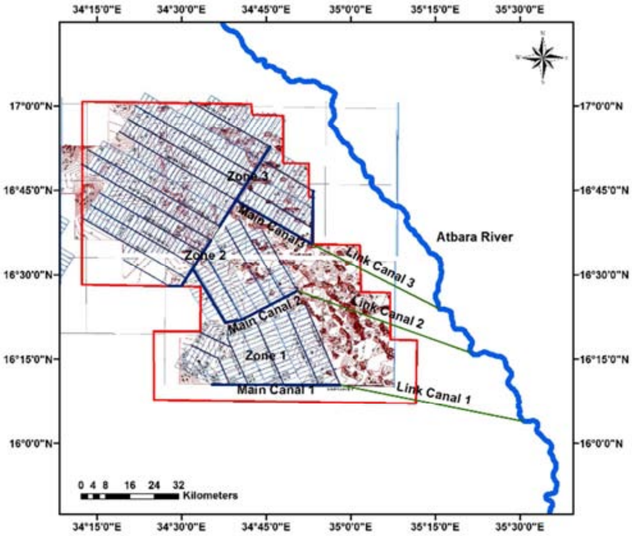

Figure 6. Irrigation network planning for the Study Area.

The irrigation canal system was designed, the total length of the canals is 3,426 km and the total irrigated areas is 419,605 hectares (94% of the arable areas). The earth works was calculated, the total volume of the excavation and filling (transferred) works were about 34,686,189 m^3 and 121,983,197 m^3 respectively. Table 2 shows the number and length of the canals and amounts of excavation and filling works. Drainage canals are planned and designed to collect and transfer the excess irrigation water from the ends of the irrigation canals to the outside of the project.

Table 2. Minors, majors, mains and link canals and the total earth work.

Canals	Numbers of canals	Canals Length (m)	Irrigated area (Hectare)	Discharge (Q) m^3/s	Earth work	
					Transferred soil (m^3)	Excavation soil (m^3)
Minors	534	2490.5	419,605	602.8	48,212,496	7,673,440
Majors	22	630.0		605.6	47,220,561	10,515,037
Mains	3	129.5		584.0	11,502,679	7,085,278
Links	3	176		607.1*	15,047,461	9,412,433
Total earth works (m^3)					121,983,197	34,686,189

* Increased by 10% as transfer losses

4. Conclusion

Soil study for the studied area concluded that 419,605 hectares could be reclaimed which represent 94% of the arable areas. Three irrigation networks have been developed and designed so that surface spate irrigation is designed with total volume of the excavation and filling (Transferred) works about 34,686,189 m^3 and 121,983,197 m^3, respectively, and a flow rate of irrigation about 670 m^3/s that exceeds 90% of the arable area with the minimum use of energy and low operating cost.

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