Improving Water Management Practices in the Rahad Scheme

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Abstract

This study aims to investigate and develop proper operational water management tools for the Rahad irrigation scheme. The Rahad project is considered as being among one of the schemes that could have a huge potential for expansion in the near future after the heightening of the Roseires Dam. The water supply sources for the Rahad scheme are the Blue Nile River and the Rahad seasonal river. The study explores options of augmenting the supply from the Rahad River during the wet season with the goal of minimizing sedimentation problems on the supply canals, reducing operation and maintenance costs associated with the Mena pumping station. Crop water requirements for the Rahad scheme were computed based on the historical cultivated areas of the different crops for the period 2000-2004. The Water Delivery Performance (WDP) Indicator for the scheme was evaluated. Frequency analysis and flow duration curves for the historical records of the Rahad seasonal stream were conducted in order to establish the yield of the Rahad River at different assurance levels. It is found that the yield from the Rahad seasonal river with 90% assurance level could be adequate to maintain an optimum performance of the irrigation system. Such proposed water management tools would improve the WDP by more than 25%. The dependence on the Rahad River during the wet season to meet the project irrigation water demands is anticipated to significantly minimize the maintenance and operation cost of diverting water from the Blue Nile.

Introduction

Studies of irrigation systems particularly in the developing countries always reveal a wide gap between expectation and reality. Several researchers in Sudan studied the deterioration and the low performance in Gezira scheme within the context of inadequate irrigation management and the need for institutional reforms. Baily and Lenton (1984) outlined a procedure for gathering and assessing information on water delivery performance of the Gezira scheme. The Rahad Irrigation project is considered among one of the scheme that could have a huge potential of expansion in the near future. The water supply sources for the Rahad scheme are the Blue Nile River and the Rahad seasonal river. Mena pumping station diverts water from the Blue Nile River to the Rahad scheme through the Rahad Supply canal. During the flood or wet season that is between August and October, the supply to the Rahad scheme is augmented from the Rahad Seasonal River. Water management and irrigation efficiency of the Rahad Scheme was studied by a number of researchers. Hamad (2006) investigated the performance oriented management approach for the Rahad irrigation system using remote sensing and GIS. The broader objective of Hamad work was to achieve a performance oriented attitude in managing irrigation systems through the development of a decision support tool that help to evaluate the in-season and overall season performance. The International Water Management Institute (IWMI) in Sudan, during the early nineties, carried out performance evaluation study for the Rahad Scheme (Shafique, 1994).

Despite such effort, there is no system based management style in the Rahad scheme and management relies on long experience of the staff. Consequently, operation decisions are observed to be fully determined by ad hoc request, personal experience, urgencies of the water users, and releasing more and probably unwanted water to minimize complaints and conflicts with politician. Such style of water management poses a huge burden and stresses on the scheme infrastructures in terms of maintenance and operation cost. As a result of poor water management, sedimentation is considered one of the most serious problems in the Rahad scheme. The carrying capacity of the irrigation system is decreased. The quantities of sediments entering the scheme during the period July to October 1996 was estimated to be 0.6 million ton. The total amount of sedimentation along the supply canal is reported to be 4.2 M m^3. It affect very much bed level slope, being reduced from 4.1 cm/km to 3.5 cm/km and the carrying capacity from 8.6 to 4.1 M m^3/day . The supply canal is subjected to continuous breaching whenever the discharges supplied by the pumps exceed 4.1 M m^3/day (Ahmed at al., 1996).

This study aims to investigate and develop proper operational water management tool for the Rahad irrigation project that could potentially improve the irrigation efficiency of the scheme and minimize the maintenance and operational cost of the water supply infrastructures. The study explore options of augmenting the supply from the Rahad seasonal river during the wet season (August-October) in order to minimize the sedimentation problems in the supply canal and the operation and maintenance cost of the pumping units.

Performance of Irrigation Systems: Concept and Assessment

There is almost a consensus that a good irrigation water supply system must be judged by three primary criteria, adequacy, timelines and equity. These characteristics will provide an understanding of the management capacity to allocate, schedule, and distribute water in an irrigation system. Other important criteria by which the health of an irrigation water supply can be judged include an efficiency measure, which is widely used in assessing the performance of the conveyance system. Generally the performance indicators of the irrigated agricultural system can be categorized into three (Bos et al., 1993): the water supply indicator; the agricultural performance indicators; and the economic, social and environmental indicators. Table 1 describes briefly the main performance indicators for an irrigation delivery system.

Table 1 Some Indicators of Irrigated Systems Performance (Hamad, 2006)

Water Supply Indicator	Agricultural Indicators	Socio-economic and Environmental
1. Efficiency Water Use Efficiency Conveyance Efficiency System Efficiency 2. Adequacy 3. Reliability 4. Dependability 5. Maintenance Indicator	1. Yield 2. Production 3. Land use	1. Sustainability 2. Productivity 3. Profitability 4. Users Participation 5. Cost

Irrigation Efficiency

The irrigation efficiency can be defined at different levels in an irrigation system. These are the conveyance efficiency, distribution efficiency, field application efficiency, and the overall project efficiency (BOS 1979, 1997):

$$Concveyance\ efficiency:\quad e_c = \frac{V_d + V_2}{V_c + V_1}$$

$$Distribution\ efficiency:\quad e_d = \frac{V_f + V_3}{V_d}$$

$$Field\ Application\ efficiency: e_a = \frac{V_m}{V_f}$$

$$\text{Pr}oject\ Overall\ Effiency:\quad e_p = \frac{V_m + V_2 + V_3}{V_c + V_1}$$

where: V_1= inflow from other sources, V_2= non-irrigation deliveries from conveyance system, V_3= non-irrigation deliveries from distribution system, V_d= volume delivered to distribution system, V_c= volume diverted or pumped from the river or source, V_f= volume furnished to the field, V_m= volume needed to maintain soil moisture above a minimum level required for the crop. If the flow from other sources $V_{1,}$ and the non-irrigation deliveries V_2 & V_3 are insignificant compared with the volume of water delivered to maintain soil moisture at the required stage of the crop, the project overall efficiency can be expressed as:

$$e_p = \frac{V_m}{V_c} = e_c\ x\ e_d\ x\ e_a$$

Adequacy

A fundamental concern of water delivery systems is to deliver irrigation water to adequately irrigate the crops, and its measure will reflect the ability of the irrigation system to supply enough water for satisfactory growth of the irrigated crops. This amount of water is a function of the irrigated area, the crop consumptive use requirements, water application losses, and the actual practices such as land preparation and salt leaching. On the other hand, the adequacy of water delivered is dependent on the availability of water supplies, specified delivery schedule or demand, the capacity of hydraulic structures to deliver water according to the schedules, and the operation and maintenance of hydraulic structures. An instructive measure of adequacy was first by Levine (1982), namely the Relative Water Supply (RWS):

$$RWS = \frac{Water\ Supplied}{Demand\,(Water\ required)} = \frac{Irrigation + Rain}{ET + Perc + Seepage}$$

Oad & Levine (1985), Oad and Padmore (1989) address the issue of the adequacy of water supplies to evaluate how well water was managed in irrigated rice fields under various supply levels. They slightly modified the RWS defined by Levine (1982), by using the effective rainfall instead of actual rainfall.

El Awad (1991) pointed out that, this definition however, neglects the fact that although the total supply during the whole season may be satisfactory, some periods of water stress may be experienced. A measure of the adequacy of water supplies must therefore reflect how the water supply pattern matches the evapotranspiration needs of the crops. To cater for this variation Lenton (1984) studied the adequacy of water supplies to non-rice irrigation systems, and defined a measure which is called the Water Delivery Performance (WDP). The measure takes into consideration the timing of water supply in relation to crop development:

$$WDP = \sum^{T} K_t \left(\frac{V_t}{V_t^*} \right)$$

Where:

V_t=actual volume of water delivered to the irrigation area during period t of the crop growing season

V^*= target volume of water to be delivered to the irrigation area during period t of the cropping season.

K_t= a weighing factor indicating the relative importance of the different crop stages during the period t. The values of K_t are normalized so that they sum up to unity over the whole season.

T= number of time periods in the season.

Clearly the WDP may take values between zero and unity or greater than unity in which case Lenton's suggested to take the reciprocal. According to Baily (1984) , the WDP can be mathematically defined as:

$$WDP = \frac{1}{n}\sum_{t=1}^{n} e(t)$$

$$e(t) = \begin{bmatrix} \dfrac{V(t)}{V^*(t)} & if \quad V(t) < V^*(t) \\ \dfrac{V^*(t)}{V(t)} & if \quad V(t) > V^*(t) \end{bmatrix}$$

Where: V(t) is the total volume of water entering the irrigation system during period t, $V^*(t)$ is the total target volume of water to be supplied to the system during time t, and n is the number of periods in the cropping season. WDP would equal 1.0 if the water delivered during each watering is equal to the crop water requirement for that watering. It would equal to zero if no water is delivered at all. The index could register both under-supply and over-supply within the 0-1 range. In their effort to capture the problem of adequacy variation with respect to time and location, particularly in large irrigation systems, Molden and Gates (1990) defined system performance relative to adequacy as the spatial and temporal average of the ratio of delivered or required amount of water:

$$P_A = \frac{1}{T}\sum^{R}\frac{1}{R}\left(\frac{Q_D}{Q_R}\right) \qquad Q_D \le Q_R$$

Where: P_A= adequacy index, Q_D= delivered amount of water, Q_R= required amount of water, R= region or sub region served by the system at time T. The index is calculated from the average of discrete quantities of Q_D and QR defined at discrete locations of the water delivery system in a region or a sub-region R, and for finite times t over T. When $Q_D > Q_R$, delivery is considered adequate regardless of the magnitude of the excess. Weighted averages could be used when it is desired to design water delivery priorities to a certain region in the system.

Description of Rahad Scheme

The Rahad Agriculture scheme was planned during the mid 1960s. Execution period began in 1973 up to 1977 when part of the Rahad Scheme was put under cultivation and the whole scheme fully operated in 1981. All the studies done on Rahad scheme revealed the area suitability for diversified pattern of cropping. The area of the scheme is well leveled and it extends on the eastern bank of the Rahad River. The total area is 126000 hectares (300,000 Fed) extending from South to North with a gentle slope of 10 cm per km, with total length of 120 km and an average width of 10-25 km. 95% of the soils in the area are heavy clay. Soils are classified as a very fine clay soils with clay percentage of 75% in the south and decreases towards the north. The infiltration rates of Rahad soil is moderately low (0.8-1.9 cm/hr). The hydraulic conductivity range from 1.7 – 4 cm/hr and the dry bulk density values range from 1.6 – 1.9 g/cm^3. Effective soil depth is (100-120 cm) approximately. The scheme lies in the semi dry zone with short rainy season from July to October. Annual rainfall increases southwards from 300 mm in the north to 400 mm in the South. Peak rainfall is in August. Evaporation from open water (E_0) is estimated to range from 3000 mm/annum (Wad Medani) in the North to 2450 mm/annum (Sennar) in the South. Highest daily evaporation was 10 mm/day in the North and 8 mm/day in the South during May. Maximum daily air temperature is 41.6 ^oC in the North during May and 41.3 ^oC in the South during April while minimum daily air temp is about 14.3 ^oC during January. Relative humidity (RH) is maximum during August reaching 67% and minimum during April about 18%. Maximum wind speed is during June and July reaching 4.9 m/sec. Table 2 summarize the climate in the Rahad Scheme.

Table 2 Climate Average in Rahad Scheme

Climate Variable	North of Scheme	South of Scheme	Month
Rainfall (mm)	300-350	350-400	July-October
Maximum daily air temperature (^oC)	41.6	41.3	May & April
Minimum daily air temperature (^oC)	14.3	14	January
Maximum Relative Humidity (RH) %	67	64	August
Minimum Relative Humidity (RH) %	18	21	April
Maximum Wind Speed (m/s)	4.9	3.6	June
Minimum Wind Speed (m/s)	2.2	2.2	October
Maximum Daily Evaporation (mm/day)	10	8	May
Total Evaporation (mm/year)	3000	2450	January-December

Crop rotation in the Rahad scheme began in 1977 with two course rotation and main the crops are cotton and groundnuts up to 1981. Tenancy holding in the Rahad Scheme is 22 Feddan for field crops, five Fed. For Vegetable crops and 10 Fed. For fodder crops. In the season 1981/82 sorghum (Dura) was introduced in the scheme for some local socio-economic reasons and the rotation become three course rotation: Cotton 11 Fed., Groundnut 6.5 Fed., and Dura 5.5 Fed. That rotation continued up to 1989 when wheat was introduced for national food security reasons and the rotation became a four course rotation: Cotton, wheat, groundnut and Dura 5.5 fed each. Vegetables, fodder and forestry are introduced in the rotation to satisfy the needs of inhabitants in the scheme. The adoption of free market economy in the scheme (1994) had its own implication on the Rahad rotation. The current situation for the future policy is to react positively to the market signals (i.e. supply, demand and prices) and the rotation in the scheme may include new crops such as Sugar cane, Maize, Sesame and Sunflower. The recommended Sowing Dates of the Main Crops in the Rahad Scheme for Groundnut is from June 1st to June 20th ; Cotton from early July to mid of August; Sorghum (Dura) between 1st to 10th of July; and Wheat between November 3rd to December 12th.

Scheme Management Organization

The scheme runs by the Rahad Agricultural Corporation (RAC), Irrigation Water Corporation and Farmers Union. The Rahad scheme is divided into nine divisions. Each division called group and administered by Agricultural Group Manager. The group manager is assisted by five field inspectors, an agricultural engineer and one plant protection specialist. Thirty water watchmen assist in supervising and operating the intermediate regulators of the minor canal and field outlet pipes and oversee the progress of irrigation and other agricultural activities in the field. The Irrigation Water Corporation is responsible of operating the main system of irrigation from the Blue Nile where the pumps are situated up to and including the off-take structures of the minor canals. Minor operation is done by the Rahad Agricultural Administration.

Water Supply Infrastructure of the Scheme

Figure (1), below shows schematic of the major water supply infrastructures of the scheme which consist of: (a) Mena Pumping station which divert water from the Blue Nile to the scheme; (b) Abu-Rakham barrage which serve as the major regulator of both the supply from

Rahad river and the Blue Nile River; (c) Supply canal from Mena to Abu Rakham; (d) a canalization system of main, major and minor canals which distribute water from Abu-Rakham to the field.

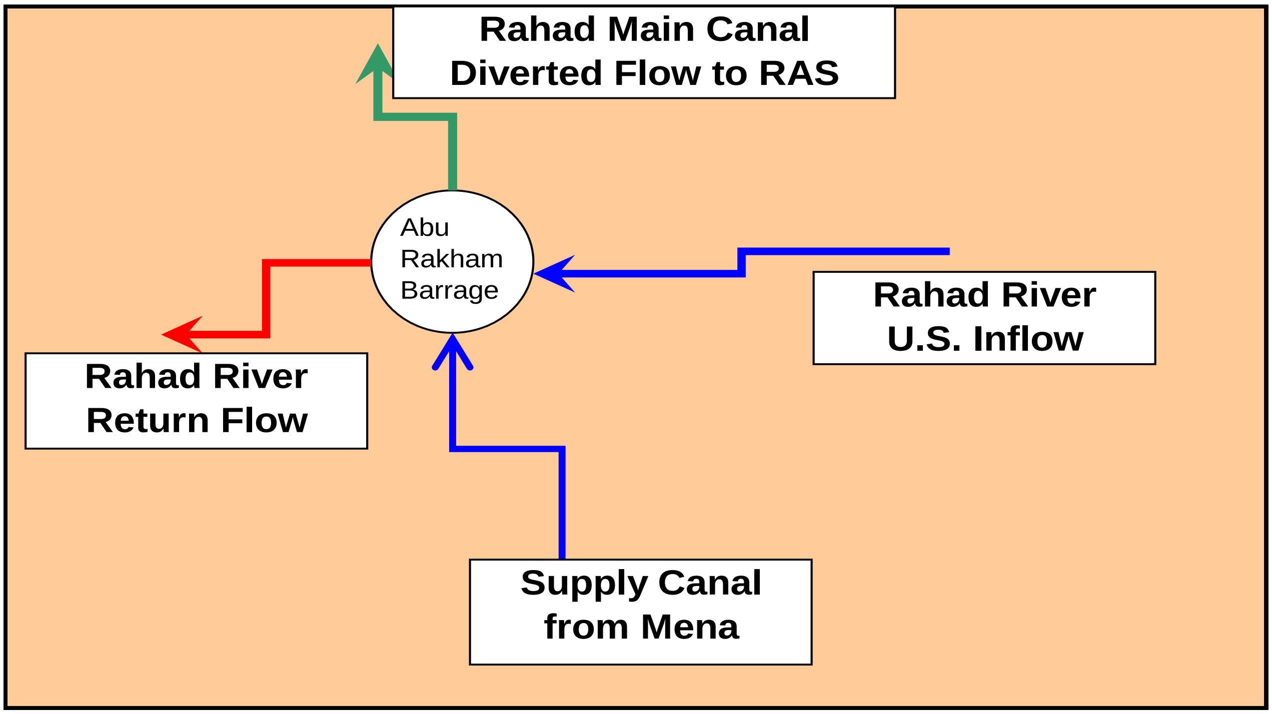

Figure 1: Schematic of the Water Supply Infrastructure (Rahad Scheme)

Mena Pump Station

Eleven electrical centrifugal pumps are suited 200 km downstream Roseries Dam on the eastern bank of the Blue Nile River for the purpose of irrigating the Rahad Agricultural Scheme. Operation head is between elevation 421.7m and 417.8m below which cavitations will take place and may cause damage to the pumps. The capacity and number of pumps was determined according to the maximum Crop Water Requirements (CWR) during the growing season. The peak CWR in the Rahad Scheme is 28 m^3/Fed/day and that figure is used in the design of all irrigation networks. The Capacity of Main Canal=228 m^3/Fed/day x 300,000 Fed = 8.4 Million m^3/day. The Capacity of the pumps is 9.55 m^3/sec per pump. The total discharges given by operating 10 pumps for 24 hrs (design capacity) are given as follows:

- Total Discharge pump capacity = 10 pumps x 9.55 m^3/sec per pump x 24 hrs/day x 3600 sec/hr = 8.25 Million m^3/day. While at low head it may reach up to 9.0 M m^3/day (10.5 m3/sec per pump). One pump is left as a reserve.

After 38 years of work, pumps situation has been deteriorated. Three pumps are out of work and the remaining eight pumps need urgent maintenance and repairs. Current operation of pumps does not exceed 20 hours per day due to power outage and lack of proper maintenance. Original design was based on 24 hrs continuous operation.

The inlet channel to Mena pumping station is 100 m long and 80 m wide. Its main function is to link the pump station to the Blue Nile River. Bed Elevation is at 413 m. Contribution of the

Blue Nile through the inlet channel and pump station is about 55% of the total seasonal consumptive use of the RAS. Seasonal sedimentation occurring during the flood was and still the main constraints which limit water availability in the RAS.

Supply Canal

The Supply canal is setup to convey discharges from pump station to the Rahad River one km upstream of Abu Rakham Barrage. It extends for 81 km from west to east with a design capacity of 105 m^3/s, water slope of 4.5 cm per km, water velocity of 0.619 m/s, bed width of 40 m and water depth of 3.6 m. The section of the can is of trapezoidal shape with side slopes 2:1, critical command of 1.72 m and full supply level maintained at elevation 432.0 m downstream the pumps. Eight bridges are set up along the supply canal. Small pumps are installed along the supply canal to irrigate some area of the Blue Nile Corporation (Total discharges of 2,000 m^3/d). Two siphons are constructed to drain rain water during the rainy season at Kilo 43 and 77. The supply canal crosses Dinder River through a Siphon at Kilo 23.

Abu Rakham Barrage

This is a diversion structure set up across the Rahad River to divert water from its normal channel into the Rahad main canal (Figure 2). Fifteen vertical sluice gates are constructed for the operation of the barrage across the Rahad natural stream. There are nine gates operated on the natural stream of the Rahad River while six gates are operated on the main canal system. Dimensions of the gates are 6m in length and 4m in width.

Figure 2: Regulators at Abu Rakham Barrage

The discharge is computed using the following equation:

$$Q = 1.431(O_t - 0.169)\sqrt{h} \qquad h \le 0.10\ m$$
$$Q = 1.178(O_t - 0.378)\sqrt{h} \qquad 0.11 \le h \le 0.25\ m$$
$$Q = 1.182\left(O_t - 0.012)\sqrt{h}\right) \qquad h \ge 0.264m$$

Where: Q is the discharge in Mm^3/day, O_t is the total underneath opening in (m) of the sluice gate and h is the head difference in (m).

Main Canal System

It extends for 101 km with a carrying capacity of 8.64 M m^3/day. The network system which is connected to the main canal consist of 215 km length of majors, 780 km of minors, 350 km of tertiary canals (Abu Ishreen) length is 4500 km. The main canal problems are the same as those of the supply canal (sedimentation).

Analysis and Results

The data collected for Rahad scheme consist of (a) historical monthly demands both requested (water indents) and actual supplied to the scheme for the Period 1987-2006; (b) Historical monthly Rahad seasonal flows and Rahad return flow after abstraction for the period 1980-2006; (c) Historical data of cultivated areas for each crop on 10-days basis for the period 2000-2004; (d) Climatological data which consist of rainfall and evaporation data on 10-days basis for the period 2000-2005; (e) Published data on crop coefficient for all the crops cultivated in the Rahad scheme; (f) Sowing dates for the crops in the Rahad scheme and (g) Capacity of the existing water supply and conveyance infrastructure of the scheme. This includes the capacity of the pumping unit at Mena, supply canal and main canals. Physical characteristics of Abu-Rakham regulators and stage-discharge relationship.

Data Pre-Screening: Supply versus Demand Analysis

To investigate the adequacy of the two water supply sources in meeting the historical irrigation demand of the scheme, the monthly supplied and requested demands (indent) were plotted and analyzed for the period 1987 to 2006 (Figures 3 to 5). It could be noted from the Figures, that the supply in some years exceed the requested demands (excess supply) and in other seasons there is a water shortage or deficit problems. The period between January 1st, 1994 to December 1999 (Figure 6), showed a continuous trend of water deficit problems in the scheme where the historical water indent or requested demand exceeds the supply at Abu-Rakham. The months of June , September, October and November are considered to be the water demand period for the crops (Figure 8). The water shortage or water stress problems normally start in the months of September, October and November. This indicate that the major water shortage is associated with the operation of Abu Rakham barrage and Mena Station, during the period which start in august and end the last week of September.

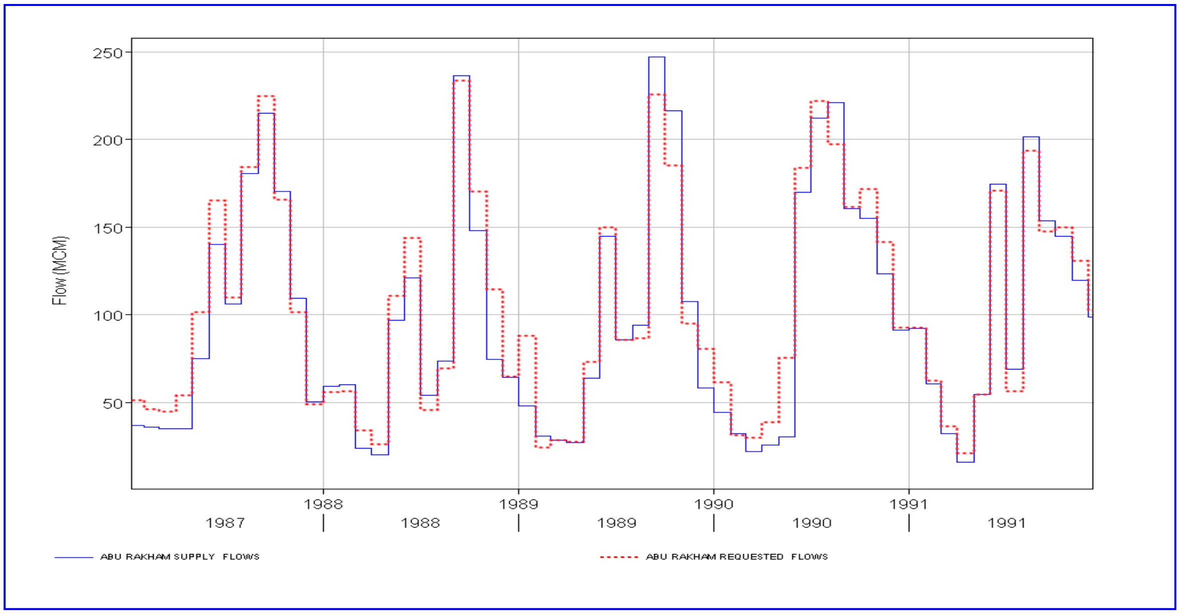

Figure 3: Supply versus Requested Demand: Abu-Rakham Station (Jan 1987 – Dec. 1991)

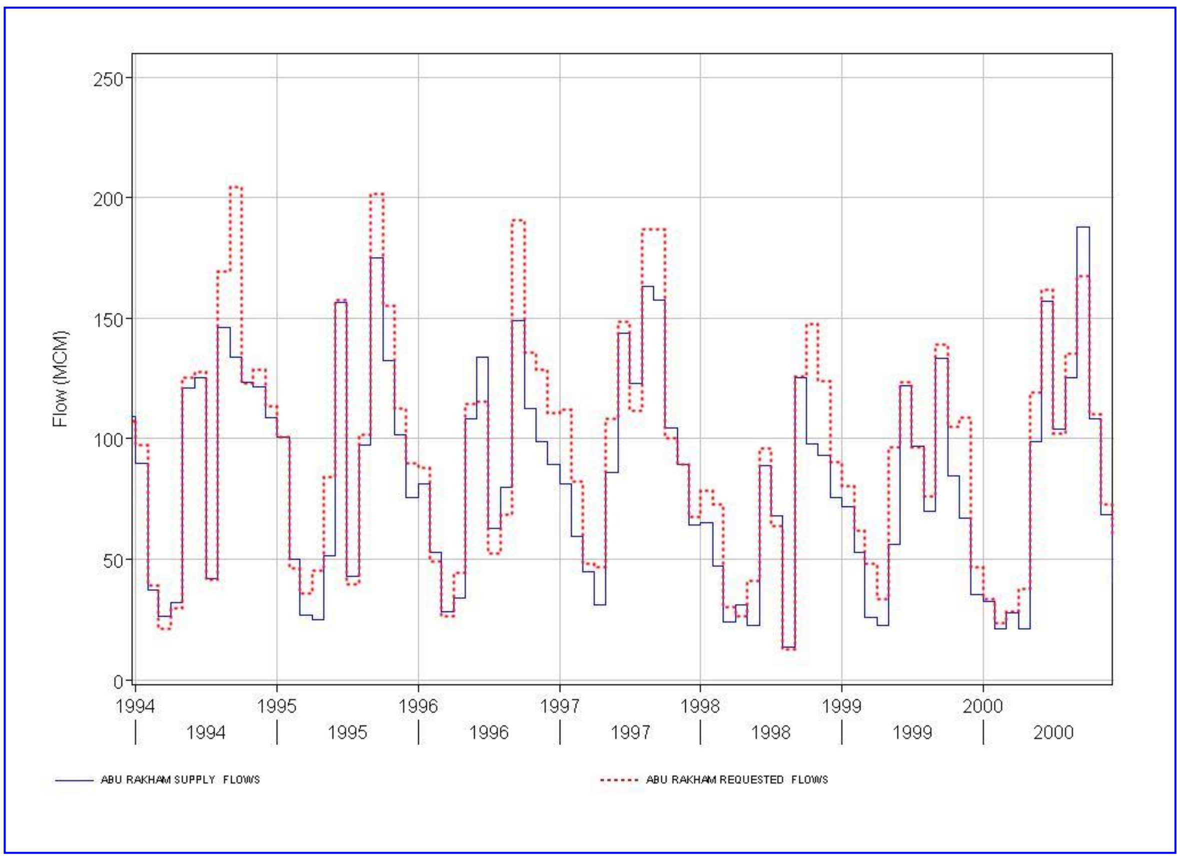

Figure 4: Supply versus Requested Demand: Abu-Rakham Station (Jan 1994 – Dec. 2000)

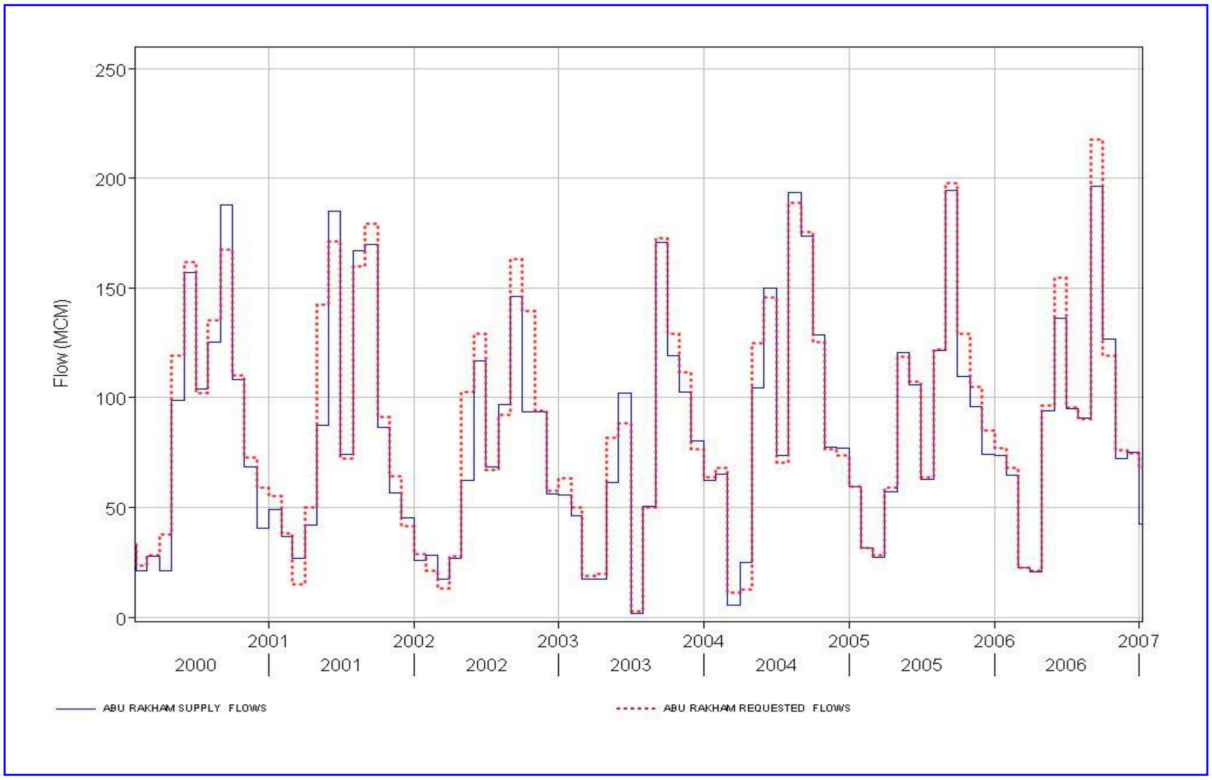

Figure 5: Supply versus Requested Demand: Abu-Rakham Station (Jan 2000 – Dec. 2006)

Estimation of Irrigation & Crop Water Requirements

To examine the water shortage problems the actual water requirements of the scheme for the years 2000-2004 were estimated based on a simple mass balance method. The mass balance equation, takes into consideration effective rainfall and actual crop water requirements or crop water uses rather than anticipated or requested demands which are based on planned irrigation areas.

The water balance method used to assess the irrigation requirements could be expressed as follows:

$$CWR = (ET_o K_c - RF)\,(Area\ Planted) + D + R + L + \Delta S$$

where: CWR represent irrigation or Crop Water Requirement, RF effective rainfall, ET_o is the reference Crop Evapotranspiration, K_c is the crop coefficient which depend on the type of crop and also varies with time, D deep percolation, R runoff, L leaching requirements and ΔS change in soil moisture storage. The central clay plane of the Sudan, where Rahad scheme is part of it, is characterized by being free from salts, flat and with high clay content. For these characters of Rahad soils, the leaching requirements, runoff and deep percolation is insignificant on water application. During each irrigation soil moisture is brought to its original level, then $\Delta S=0$ and thus the formula becomes:

$$CWR = (ET_o K_c - RF)\,(Area\ Planted)$$

An Excel-Spreadsheet was developed to compute the crop water requirements for the Rahad scheme on monthly basis. The CWR calculations are tabulated for the Years 2000-2004 as shown in Table 3. It can be noted from the Table that, the months of August, September, October and November form the period of maximum demand and water shortage or water stress problems, with September and October considered to be the peak demand months for the growing season. On average annual basis about 45% of the water supplied to the scheme is diverted from the Rahad River at Abu-Rakham Barrage during the wet season of July to October and 55% is diverted from the Blue Nile River through Mena Pumping station. As could be realized from the Table, the total annual release from Abu-Rakham to the main canal of the project, always exceeds the net crop water requirements of the scheme with an average factor of 1.43 (i.e. Average Annual Release to the main Canal of the scheme = 1.43 x Average Net Annual Crop Water requirement). This includes the water requirements for the forested areas. Considering conveyance losses and deep percolation losses such annual quantity of supplied water should be adequate to meet scheme water demands and account for more than 30% losses. This implies that, the total annual water supplied to the scheme is adequate but the timing and management of water supply sources are the main causes of water deficit and water stresses problems during the growing seasons of the crop. It could also be noted from the table that the total annual yield of the Rahad river alone exceed the water demand for the scheme by a factor than ranges from 1.4 to 3.2. This indicate that through proper management of the regulators at Abu-Rakham Barrage the supply from Rahad seasonal river could be augmented during the months of August, September and October to meet the majority of the water demand of the scheme with minimum dependence from Mena Pump station which could possibly be functioning during the dry season only and/or as a backup to supplement the Rahad during low yield years. Such proposed operational rule for the scheme, would decrease the operation and maintenance cost of the pumping station and could potentially reduce the siltation and sediment dredging operation on the supply canal. Considering the fact that, the Blue Nile River carries high concentration of sediment during the months of August to October, minimizing the Mena Pumping operation during this period, could potentially reduce the quantity of sediments entering the supply canal of the Rahad scheme.

Table 3 Crop-Water Requirements Computations and Comparison of Supply versus Demand Rahad Irrigation Scheme for the Period 2000-2004

	Coulmn (1)	Column (2)	Column (3)	Column(4)	Column (5)	Colum (6)	Colum(6)
Month	$ET_o \sum_{1}^{n} K_c(crop\ J) \times Area\ (crop\ J)$	RF x Total Monthly Planted Area	CWR = Column(1)-Column(2)	Mena Supply	Rahad Inflow	Rahad Return Flow	Actual Supply
	Million Cubic Meters	Million Cubic Meters	Million Cubic Meters	MCM	MCM	MCM	MCM
June	31.0	5.6	25.5	97.3	0.0	0.0	98.9
July	90.6	30.4	60.2	61.0	159.3	8.7	157.2
August	156.1	48.0	108.0	2.0	344.2	152.5	103.9
Sept	198.4	23.4	175.0	4.5	377.7	156.7	125.3
October	178.5	13.8	164.8	8.1	236.5	79.9	178.6
November	114.5	0.0	114.5	49.3	112.5	39.0	108.2
Dec.	45.6	0.0	45.6	57.4	0.0	0.0	58.5
Jan	43.8	0.0	43.8	30.6	0.0	0.0	35.5
Feb	33.2	0.0	33.2	34.4	0.0	0.0	32.5
March	14.8	0.0	14.8	21.9	0.0	0.0	21.1
April	7.4	0.0	7.4	26.9	0.0	0.0	27.6
May	13.6	0.0	13.6	19.3	0.0	0.0	21.3
Year 2000	927.5	121.2	806.3	412.6	1230.2	436.6	968.4
June	14.6	1.5	13.1	88.4	0.0	0.0	87.4
July	71.2	26.1	45.0	68.0	144.0	32.1	185.1
August	166.1	66.7	99.4	1.3	377.8	267.3	74.2
Sept	209.3	29.6	179.8	0.6	448.7	262.9	166.8
October	177.0	7.3	169.6	0.0	188.5	27.6	169.8
November	106.9	0.0	106.9	45.2	30.1	0.0	86.6
Dec.	23.4	0.0	23.4	47.2	5.4	0.0	56.6
Jan	21.2	0.0	21.2	43.8	0.0	0.0	40.7
Feb	20.3	0.0	20.3	52.8	0.0	0.0	49.0
March	15.3	0.0	15.3	46.3	0.0	0.0	36.8
April	2.8	0.0	2.8	33.8	0.0	0.0	26.6
May	9.4	0.0	9.4	50.7	0.0	0.0	42.1
Year 2001	837.5	131.2	706.3	478.1	1194.4	589.9	1021.4
June	14.6	4.4	10.2	82.1	0.0	0.0	62.3
July	71.2	54.4	16.7	81.5	87.3	23.7	116.8
August	166.1	134.2	31.9	3.1	287.1	238.1	68.5
Sept	209.3	38.0	171.3	3.9	294.5	229.4	96.7
October	177.0	1.6	175.4	70.1	128.6	44.6	146.0
November	106.9	0.0	106.9	87.3	0.0	0.0	93.6
Dec.	23.4	0.0	23.4	89.9	0.0	0.0	93.5
Jan	21.2	0.0	21.2	43.3	0.0	0.0	45.5
Feb	2.3	0.0	2.3	30.0	0.0	0.0	25.9
March	0.5	0.0	0.5	27.9	0.0	0.0	28.3
April	0.7	0.0	0.7	22.9	0.0	0.0	17.4
May	2.4	0.0	2.4	33.5	0.0	0.0	26.6
Year 2002	795.6	232.5	563.1	575.4	797.5	535.7	820.9
June	11.9	5.1	6.8	71.6	0.0	0.0	61.4
July	74.2	41.9	32.3	14.4	322.8	218.0	101.9
August	116.7	99.4	17.4	2.6	580.0	579.1	1.7
Sept	148.6	28.1	120.5	1.4	587.1	536.9	50.5
October	139.7	1.2	138.5	2.5	249.6	81.1	170.9
November	105.7	0.0	105.7	80.4	0.0	0.0	119.1
Dec.	46.8	0.0	46.8	101.2	0.0	0.0	102.4
Jan	41.8	0.0	41.8	56.5	0.0	0.0	56.2
Feb	26.0	0.0	26.0	54.3	0.0	0.0	55.7
March	2.8	0.0	2.8	49.4	0.0	0.0	46.2
April	0.7	0.0	0.7	21.7	0.0	0.0	17.5
May	2.4	0.0	2.4	23.6	0.0	0.0	17.1
Year 2003	717.3	175.7	541.6	479.5	1739.4	1415.1	800.6
June	17.2	5.7	11.5	109.7	0.0	0.0	104.5
July	70.4	43.6	26.8	29.2	211.3	90.8	149.7
August	152.8	129.7	23.1	1.6	427.0	341.2	73.9
Sept	194.4	36.7	157.7	2.0	251.6	80.6	193.7
October	182.0	1.6	180.4	20.0	213.3	97.9	173.7
November	149.1	0.0	149.1	113.8	6.2	6.2	128.5
Dec.	71.6	0.0	71.6	77.5	0.0	0.0	77.5
Jan	52.3	0.0	52.3	82.5	0.0	0.0	80.3
Feb	36.2	0.0	36.2	66.4	0.0	0.0	62.3
March	3.1	0.0	3.1	68.6	0.0	0.0	65.0
April	0.7	0.0	0.7	14.2	0.0	0.0	5.3
May	2.3	0.0	2.3	31.9	0.0	0.0	24.9
Year 2004	932.1	217.4	714.8	617.3	1109.4	616.7	1139.2

Yield Frequency Analysis for the Rahad Seasonal River

To estimate the reliable yield for the Rahad River, frequency analysis for daily time series data (1980-2006) is conducted. Flow duration curves for each day of the period July 1st to October 31st is constructed. The corresponding yields at different assurance levels were estimated from the flow duration curve for each day of the wet period. The decadal yield is then estimated by adding the up the daily yields for the 10 days period. Figure 6 shows the computed Rahad yields at different assurance level. Summary of the results are shown in Table 4.

Figure 6: Rahad Yield at Different Assurance Levels

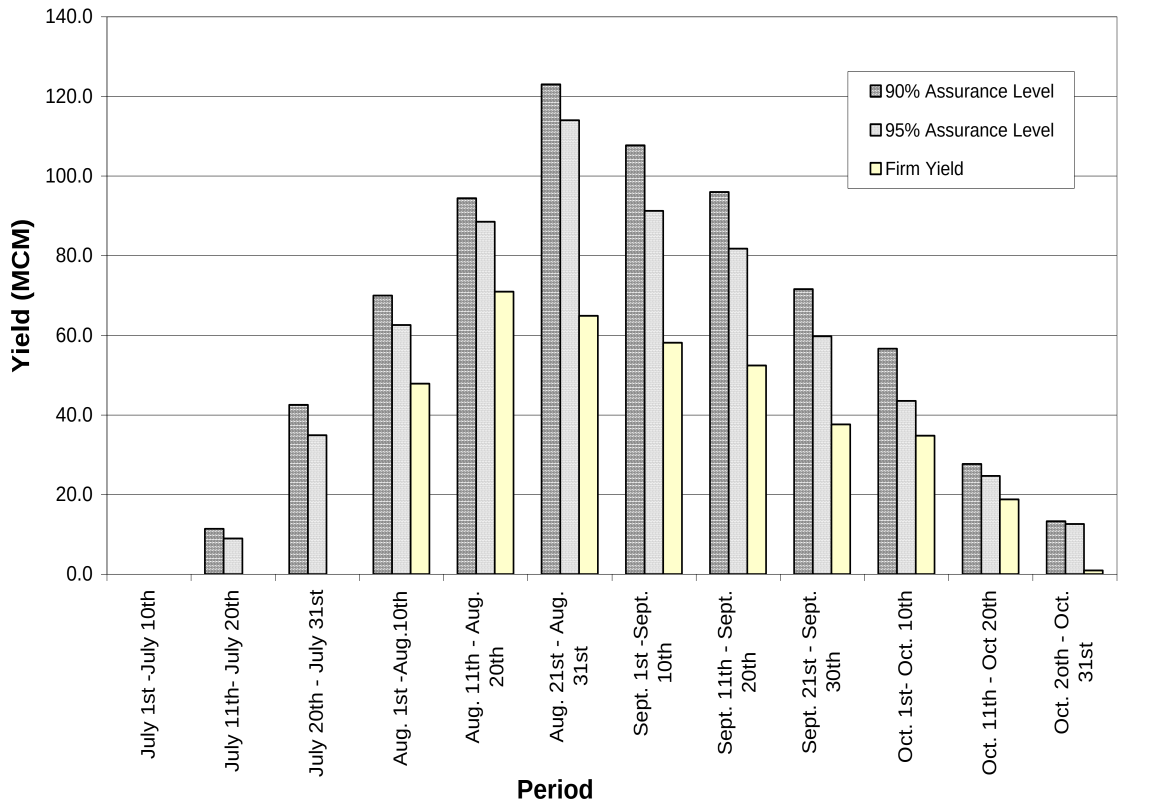

Table 4 Yield Analysis Results for the Rahad River

Decedal Period	Yield From Rahad River at Different Assurance Levels (MCM)						Net Water Requirement for Rahad Scheme (MCM)						
	Average	80%	85%	90%	95%	100%	Yr. 2000	Yr. 2001	Yr. 2002	Yr. 2003	Yr. 2004	Yr. 2005	Average
July 1st -July 10th	38.5	2.9	0.0	0.0	0.0	0.0	21.3	10.7	10.7	18.6	15.4	19.1	16.0
July 11th- July 20th	65.6	22.5	0.0	11.4	9.0	0.0	30.3	21.9	21.9	25.4	23.2	27.6	25.0
July 20th - July 31st	120.2	58.3	0.0	42.5	34.9	0.0	39.0	38.6	38.6	30.3	31.7	34.1	35.4
Aug. 1st -Aug.10th	107.0	81.2	76.1	**70.0**	62.6	47.8	47.6	50.4	50.4	35.4	46.3	40.1	45.0
Aug. 11th - Aug. 20th	120.8	103.2	99.6	**94.4**	88.5	71.0	51.6	54.3	54.3	38.0	49.8	43.3	48.6
Aug. 21st - Aug. 31st	143.9	136.3	132.7	**123.0**	114.0	64.9	56.8	61.3	61.3	43.3	56.7	48.8	54.7
Sept. 1st -Sept. 10th	133.0	126.5	116.5	**107.7**	91.3	58.2	64.4	68.6	68.6	47.9	62.8	54.0	61.1
Sept. 11th - Sept. 20th	130.7	114.5	109.2	**95.9**	81.7	52.4	66.7	69.9	69.9	49.4	64.7	56.0	62.8
Sept. 21st - Sept. 30th	113.0	90.6	80.6	**71.6**	59.7	37.6	67.3	70.8	70.8	51.2	67.0	57.3	64.1
Oct. 1st- Oct. 10th	94.2	70.7	62.4	56.6	43.5	34.8	62.6	62.9	62.9	47.7	62.2	52.7	58.5
Oct. 11th - Oct 20th	64.6	35.1	31.5	27.7	24.7	18.8	59.9	59.1	59.1	46.3	60.3	50.3	55.8
Oct. 2oth - Oct. 31st	49.5	20.6	16.3	13.3	12.6	0.9	56.0	55.0	55.0	45.7	59.5	47.9	53.2

As could be realized from the Table, Based on 90% assurance level, the yield of the Rahad seasonal river is adequate to meet the irrigation demand for the Rahad scheme for the period

August 1^{st} to Sept 30^{th}. For 80% Assurance level the Rahad yield is adequate to meet the demand for the period July 20^{th} to October 10^{th}. For the purpose of this study the 90% assurance level is selected as the design criteria for the proposed operation rule of the scheme.

The analysis of irrigation water supply adequacy is applied to evaluate if enough quantity of water is delivered when it is required. The WDP is an index for evaluation of water delivery performance (Baily 1984). The WDP takes into account both the actual and the target quantity and timing of water supply. The weighted method of computing WDP (Lenton -1984) is implemented to evaluate the adequacy of Rahad Irrigation scheme. The weighted factor K_t is taken as the ratio of CWR during the time period under consideration to the total annual CWR. The results of Irrigation Adequacy analysis are shown in Table (5) below.

Table 5 Water Delivery Performance Computation Existing Condition for the Period 2000-2004

	Coulmn (1)	Column (2)	Column (3)	Column(4)	Column (5)	Colum (6)
Month	$ET_o \sum_{1}^{n} K_C(crop\ J)\ x\ Area\ (crop\ J)$	RF x Total Monthly Planted Area	CWR =1.15x Column(1) - Column(2)	Actual Supply	$w_i = \frac{CWR_i}{\sum_{i=1}^{12} CWR_i}$	WDP
	Million Cubic Meters	Million Cubic Meters	Million Cubic Meters	MCM	MCM	MCM
June	31.0	5.6	30.1	98.9	0.03	1.0
July	90.6	30.4	73.8	157.2	0.08	3.7
August	156.1	48.0	131.5	103.9	0.14	11.0
Sept	198.4	23.4	204.7	125.3	0.22	13.3
October	178.5	13.8	191.6	178.6	0.20	18.9
November	114.5	0.0	131.6	108.2	0.14	11.4
Dec.	45.6	0.0	52.4	58.5	0.06	5.0
Jan	43.8	0.0	50.3	35.5	0.05	3.7
Feb	33.2	0.0	38.2	32.5	0.04	3.4
March	14.8	0.0	17.0	21.1	0.02	1.4
April	7.4	0.0	8.5	27.6	0.01	0.3
May	13.6	0.0	15.6	21.3	0.02	1.2
Year 2000	**927.5**	**121.2**	**945.4**	**968.4**	**1.00**	**74.3**
June	14.6	1.5	15.3	87.4	0.02	0.3
July	71.2	26.1	55.7	185.1	0.07	2.0
August	166.1	66.7	124.3	74.2	0.15	8.9
Sept	209.3	29.6	211.2	166.8	0.25	20.0
October	177.0	7.3	196.2	169.8	0.24	20.4
November	106.9	0.0	123.0	86.6	0.15	10.4
Dec.	23.4	0.0	26.9	56.6	0.03	1.5
Jan	21.2	0.0	24.4	40.7	0.03	1.8
Feb	20.3	0.0	23.3	49.0	0.03	1.3
March	15.3	0.0	17.6	36.8	0.02	1.0
April	2.8	0.0	3.3	26.6	0.00	0.0
May	9.4	0.0	10.8	42.1	0.01	0.3
Year 2001	**837.5**	**131.2**	**831.9**	**1021.4**	**1.00**	**68.2**
June	14.6	4.4	12.4	62.3	0.02	0.4
July	71.2	54.4	27.4	116.8	0.04	0.9
August	166.1	134.2	56.8	68.5	0.08	6.9
Sept	209.3	38.0	202.7	96.7	0.30	14.2
October	177.0	1.6	202.0	146.0	0.30	21.4
November	106.9	0.0	123.0	93.6	0.18	13.7
Dec.	23.4	0.0	26.9	93.5	0.04	1.1
Jan	21.2	0.0	24.4	45.5	0.04	1.9
Feb	2.3	0.0	2.6	25.9	0.00	0.0
March	0.5	0.0	0.6	28.3	0.00	0.0
April	0.7	0.0	0.9	17.4	0.00	0.0
May	2.4	0.0	2.8	26.6	0.00	0.0
Year 2002	**795.6**	**232.5**	**682.4**	**820.9**	**1.00**	**60.6**
June	11.9	5.1	8.6	61.4	0.01	0.2
July	74.2	41.9	43.4	101.9	0.07	2.9
August	116.7	99.4	34.9	1.7	0.05	0.3
Sept	148.6	28.1	142.7	50.5	0.22	7.8
October	139.7	1.2	159.4	170.9	0.25	22.9
November	105.7	0.0	121.5	119.1	0.19	18.3
Dec.	46.8	0.0	53.9	102.4	0.08	4.4
Jan	41.8	0.0	48.0	56.2	0.07	6.3
Feb	26.0	0.0	29.9	55.7	0.05	2.5
March	2.8	0.0	3.2	46.2	0.00	0.0
April	0.7	0.0	0.9	17.5	0.00	0.0
May	2.4	0.0	2.8	17.1	0.00	0.1
Year 2003	**717.3**	**175.7**	**649.2**	**800.6**	**1.00**	**65.6**
June	17.2	5.7	14.0	104.5	0.02	0.2
July	70.4	43.6	37.3	149.7	0.04	1.1
August	152.8	129.7	46.1	73.9	0.05	3.4
Sept	194.4	36.7	186.9	193.7	0.22	21.1
October	182.0	1.6	207.8	173.7	0.24	20.3
November	149.1	0.0	171.4	128.5	0.20	15.0
Dec.	71.6	0.0	82.3	77.5	0.10	9.1
Jan	52.3	0.0	60.2	80.3	0.07	5.3
Feb	36.2	0.0	41.6	62.3	0.05	3.2
March	3.1	0.0	3.5	65.0	0.00	0.0
April	0.7	0.0	0.9	5.3	0.00	0.0
May	2.3	0.0	2.6	24.9	0.00	0.0
Year 2004	**932.1**	**217.4**	**854.6**	**1139.2**	**1.00**	**78.8**

Proposed Operational Rule for Improving the Water Management of the Scheme

The proposed water management and operational rule entirely relay on the Rahad seasonal river to supply the irrigation demands during the month of July, August and September. From Table (4), the yield from the Rahad river at 90% assurance level for the months of July, August and September are 53.4, 287.4 and 275.2 MCM respectively. Such quantity of water would be available to meet the irrigation demands during this period. Any surplus or excess water could be returned to the Rahad River through the regulators at Abu Rakham Barrage. In the proposed scenario, the supply from Mena pumping station would be ceased during the months of July to September (season of high sediment concentration at the Blue Nile River). For the Month of October, it is anticipated that Mena pumping station would be operational with half capacity (that is 5 pumps for 20 Days continuous operation). Such a supply from Mena station would add 80 MCM to the 90% assurance yield of 97.6 MCM from the Rahad River making a total supply of 178 MCM for October. Summary of the proposed operational rules for the scheme is described in Table (6) below.

Table 6 Revised Operational Rule for the Scheme during the period July to October

Month	Rahad Yield 90% Assurance (MCM)	Supply from Mena (MCM)	Total supply (MCM)	Remarks
July	53.4	0	53.4	No supply from Mena station to the scheme
August	287.4	0	287.4	No supply from Mena station to the scheme
Sept.	275.2	0	275.2	No supply from Mena station to the scheme
October	97.6	80	177.6	Operate 5 pumps for 20 days

Based on the revised operational rules, the WDP for the scheme is computed for the period 2000 to 2004 as shown in Table (7) and the WDP under both existing conditions and proposed scenario are then compared as presented in Figure (7).

Year	WDP % Existing	WDP% Proposed	% Improvement
2000	74.3	87.6	17.8
2001	68.2	84.9	24.6
2002	60.6	85.3	40.7
2003	65.6	87.9	34.0
2004	78.8	85.3	8.3
Average	69.5	86.2	25.1

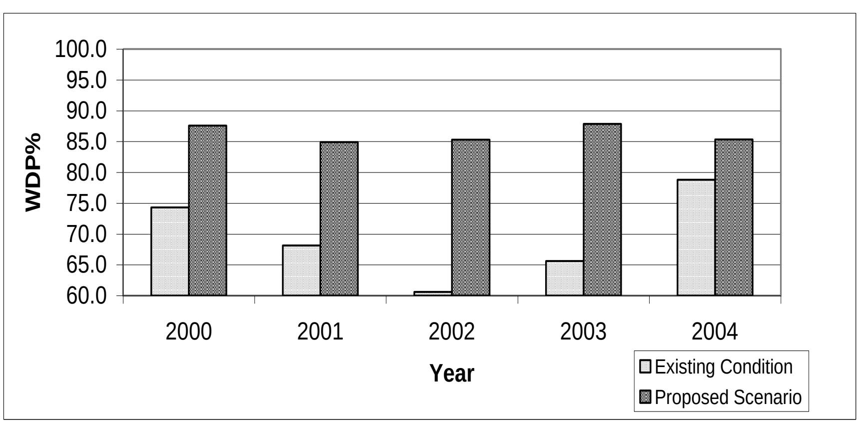

Figure (7): Comparison of Water Delivery Performance for Existing and Proposed Operational Rules

Table 7 Water Delivery Performance Computation Proposed Operation Rule

	Coulmn (1)	Column (2)	Column (3)	Column(4)	Column (5)	Colum (6)
Month	$ET_o \sum_{1}^{n} K_C(crop\ J)\ x\ Area\ (crop\ J)$	RF x Total Monthly Planted Area	CWR =1.15x Column(1) - Column(2)	Proposed Supply	$w_i = \frac{CWR_i}{\sum_{i=1}^{12} CWR_i}$	WDP
	Million Cubic Meters	Million Cubic Meters	Million Cubic Meters	MCM	MCM	MCM
June	31.0	5.6	30.1	98.9	0.03	1.0
July	90.6	30.4	73.8	53.9	0.08	5.7
August	156.1	48.0	131.5	131.5	0.14	13.9
Sept	198.4	23.4	204.7	204.7	0.22	21.7
October	178.5	13.8	191.6	177.6	0.20	18.8
November	114.5	0.0	131.6	108.2	0.14	11.4
Dec.	45.6	0.0	52.4	58.5	0.06	5.0
Jan	43.8	0.0	50.3	35.5	0.05	3.7
Feb	33.2	0.0	38.2	32.5	0.04	3.4
March	14.8	0.0	17.0	21.1	0.02	1.4
April	7.4	0.0	8.5	27.6	0.01	0.3
May	13.6	0.0	15.6	21.3	0.02	1.2
Year 2000	**927.5**	**121.2**	**945.4**	**968.4**	**1.00**	**87.6**
June	14.6	1.5	15.3	87.4	0.02	0.3
July	71.2	26.1	55.7	53.9	0.07	6.5
August	166.1	66.7	124.3	124.3	0.15	14.9
Sept	209.3	29.6	211.2	211.2	0.25	25.4
October	177.0	7.3	196.2	177.6	0.24	21.3
November	106.9	0.0	123.0	86.6	0.15	10.4
Dec.	23.4	0.0	26.9	56.6	0.03	1.5
Jan	21.2	0.0	24.4	40.7	0.03	1.8
Feb	20.3	0.0	23.3	49.0	0.03	1.3
March	15.3	0.0	17.6	36.8	0.02	1.0
April	2.8	0.0	3.3	26.6	0.00	0.0
May	9.4	0.0	10.8	42.1	0.01	0.3
Year 2001	**837.5**	**131.2**	**831.9**	**1021.4**	**1.00**	**84.9**
June	14.6	4.4	12.4	62.3	0.02	0.4
July	71.2	54.4	27.4	27.4	0.04	4.0
August	166.1	134.2	56.8	56.8	0.08	8.3
Sept	209.3	38.0	202.7	202.7	0.30	29.7
October	177.0	1.6	202.0	177.6	0.30	26.0
November	106.9	0.0	123.0	93.6	0.18	13.7
Dec.	23.4	0.0	26.9	93.5	0.04	1.1
Jan	21.2	0.0	24.4	45.5	0.04	1.9
Feb	2.3	0.0	2.6	25.9	0.00	0.0
March	0.5	0.0	0.6	28.3	0.00	0.0
April	0.7	0.0	0.9	17.4	0.00	0.0
May	2.4	0.0	2.8	26.6	0.00	0.0
Year 2002	**795.6**	**232.5**	**682.4**	**820.9**	**1.00**	**85.3**
June	11.9	5.1	8.6	61.4	0.01	0.2
July	74.2	41.9	43.4	43.4	0.07	6.7
August	116.7	99.4	34.9	34.9	0.05	5.4
Sept	148.6	28.1	142.7	142.7	0.22	22.0
October	139.7	1.2	159.4	177.6	0.25	22.0
November	105.7	0.0	121.5	119.1	0.19	18.3
Dec.	46.8	0.0	53.9	102.4	0.08	4.4
Jan	41.8	0.0	48.0	56.2	0.07	6.3
Feb	26.0	0.0	29.9	55.7	0.05	2.5
March	2.8	0.0	3.2	46.2	0.00	0.0
April	0.7	0.0	0.9	17.5	0.00	0.0
May	2.4	0.0	2.8	17.1	0.00	0.1
Year 2003	**717.3**	**175.7**	**649.2**	**800.6**	**1.00**	**87.9**
June	17.2	5.7	14.0	104.5	0.02	0.2
July	70.4	43.6	37.3	37.3	0.04	4.4
August	152.8	129.7	46.1	46.1	0.05	5.4
Sept	194.4	36.7	186.9	186.9	0.22	21.9
October	182.0	1.6	207.8	177.6	0.24	20.8
November	149.1	0.0	171.4	128.5	0.20	15.0
Dec.	71.6	0.0	82.3	77.5	0.10	9.1
Jan	52.3	0.0	60.2	80.3	0.07	5.3
Feb	36.2	0.0	41.6	62.3	0.05	3.2
March	3.1	0.0	3.5	65.0	0.00	0.0
April	0.7	0.0	0.9	5.3	0.00	0.0
May	2.3	0.0	2.6	24.9	0.00	0.0
Year 2004	**932.1**	**217.4**	**854.6**	**1139.2**	**1.00**	**85.3**

Summary and Conclusion

The results of the water demand versus supply for the Rahad irrigation scheme indicates water shortage and water stress problems during the growing season of August to October. Such water stress problems are mainly due to poor water management. It is found that the annual yield of the Rahad River at 90% assurance level could be adequate to meet the water demand of the scheme during the period of July to October. The Water Delivery Performance of the irrigation system under both existing and future proposed operational rules were evaluated. On average the WDP under existing conditions for the period 2000-2004 is found to be 69%. The proposed operational rules relies entirely on the yield from the Rahad river during the period July 1st to September 30th during which the Mena pumping station would be non-operational and the pumps would only be scheduled to operate during the month of October with half capacity (5 pumps) for a period of 20 days. Based on the proposed operational rule, the WDP for the period 2000-2004 is recalculated and the average WDP for the period is found to be 86% which reflects an improvement of about 25% over the existing situation. Such a proposed operation rule would relieve the burden on the stressed pumping unit and could potential reduce the maintenance cost of the pumping units and dredging operation on the supply canal.

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