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Hydro-environmental impact of Khor Arbaat Dam, Eastern Sudan

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To improve water supply services in Port Sudan City (Sudan), a dam with storage capacity of 16 Mm^3 was established at the upper gorge of the Khor Arbaat catchment area, which generates runoff that contributes to the sedimentation of the dam at an average rate of about 6% annually. At present (2021), the storage capacity of the dam is reduced by 69% of its original design capacity. Without interventions, the dam is expected to continue silting up reducing its capacity to 94% of the original design capacity by year 2044. Although the dam has reduced the amount of runoff that reaches the alluvium aquifer and has caused groundwater recession downstream, the continuous sedimentation and reduction of the dam's storage capacity mean the amount of water that could flow out would gradually increase. Despite its sedimentation, the dam has provided groundwater recharge 1 km upstream of the dam resulting in a rise of 2 m in groundwater level and enabled irrigation of 85% of the arable land. Comparatively, a drop of 1.8 m was observed in groundwater level at 5 km upstream of the dam, with irrigation of only 33% of the arable land. Also, the interception of the base-flow/underflow by the dam, has contributed to the recession of groundwater downstream. These observations can help optimize the use of this resource; by reducing evaporation losses and maximizing the benefit from the reservoir's available storage through the intensification of pumping during the winter period (October-March) when evaporation is comparatively low and reservoir storage can be replenished by winter runoff. Beyond technical fixes (and in the long term), management of water resources in the Khor Arbaat should consider the catchment area as a whole and in an overall framework of Integrated Water Resources Management (IWRM).

Key words: Base-flow, groundwater, integrated water resources management, irrigated land, sedimentation, runoff.

INTRODUCTION

The Red Sea State (Eastern Sudan) is a hyper-arid area where annual rainfall is erratic and variable, rarely exceeding 100 mm, and where vegetation cover is sparse and nomadic pastoralism is frequently practiced (FAO, 1985). Among the three states (Gedarif, Kassala and Red Sea), which form the Eastern Region (Sudan), the Red

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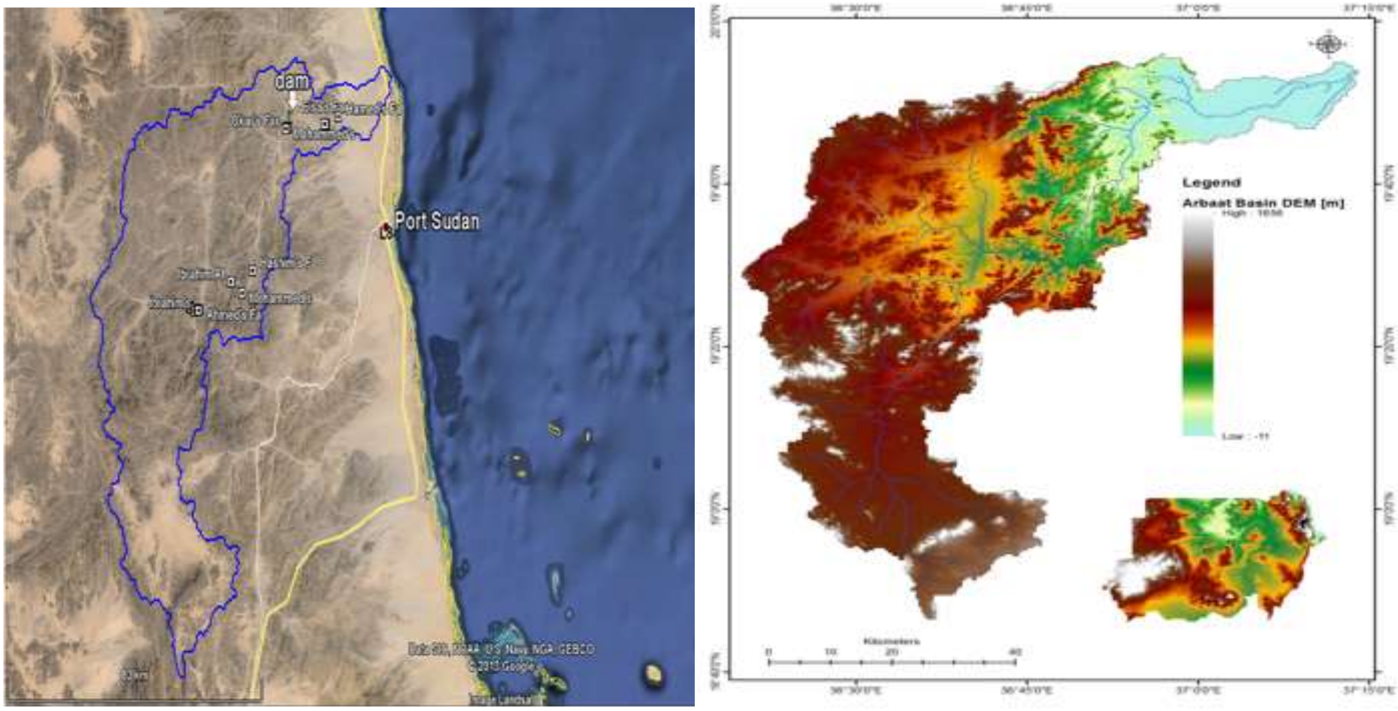

Figure 1. Location of the dam, Port Sudan City, boundary and DEM of the Khor Arbaat catchment area, Sudan.

Table 1. Water supply demand, Port Sudan City, Sudan.

Category	Year				
	2020	**2025**	**2030**	**2035**	**2040**
Population	648,300	758,800	888,300	1,039851	1,217,222
Water demand (l/c/d)	87	109	136	170	212
Water demand (m^3/day)	56,402	82,709	120,809	176775	258051

Sea State is the poorest in agricultural potential, water resources and livestock (Abdel Ati, 2015). Combined with temporal and spatial variability of water resources, the Red Sea State suffers from recurrent drought events, which have resulted in water supply shortages and increased vulnerability of the population's livelihoods in the whole state (Khogali, 2009). Port Sudan City is the capital of the Red Sea State (Figure 1) and is inhabited by about 650,000 persons (Table 1). This constitutes about 44% of the state's population. The city has been growing rapidly during the last decade(s) and this has led to large uncertainties as to the actual current population number and the growth rate. In an absence of resolute population and growth rate numbers, an average annual growth rate of 3.2% in the urban centers in Sudan, is used for projection of the population in Port Sudan City up to 2040 (Table 1). On the other hand, projection of the water demand is based on the national (Sudan) water, sanitation and hygiene strategy (Newtwch Consulting Group, 2018), which assigns an inclusive water consumption rate of 87 L per capita per day (l/c/d) for the urban centers in Sudan. However, due to the rapid growth and progressive improvement of the industrial, commercial, housing and the general socioeconomic conditions, projection of the water demand considers an increase of 5% yearly in the daily per capita consumption in Port Sudan City (Table 1). The city contains the country's main port and is one of the largest commercial centers in Eastern Sudan. However, water shortage is one of the key problems facing Port Sudan City over the last decades.

Water shortage in the city is caused by demand outstripping supply as a result of rapid population growth which is caused by increased rural-urban migration and urbanization, the spread of shanty settlements around the city and growing camps of internally displaced people (Mott McDonald, 2016; HydroNova, 2018). Water shortage is further aggravated by the declining availability of water resources (surface and groundwater) in the Khor Arbaat area which is the main water supply source to Port Sudan City. Efforts to improve and/or sustain the city's water supply from the Khor Arbaat catchment area are continuing. A number of water resources assessment studies were conducted in the area (Hussein, 1975; Rhein Rhur, 1989; El Sheikh et al., 2009; Akode and Fadallabi, 1994; Yousif and Abdo, 2003; Taha, 2020; Ali et al., 2013; Mott McDonald, 2016; HydroNova, 2018). These studies show discrepancies in annual aquifer recharge. In spite of these discrepancies, it is known that the aquifer's sustainable yield (Meyland, 2011; Maimone, 2004) is short of meeting the city's water demand (Table 1). To assist in solving the city's water supply problems, a dam with a total storage capacity of 16 million cubic meter (Mm^3) was built in 2003 by the then National Water Corporation, Sudan (now the Drinking Water and Sanitation Unit). The dam is located 3.2 km upstream of the upper gorge (gate) at the lower side of the Khor Arbaat catchment area, which is about 40 km northwest of Port Sudan City (Figure 1).

Khor Arbaat dam is an example of reservoirs in arid and semi-arid regions where seasonal (ephemeral) streams (also known as Khors or Wadis) create challenges in meeting water supply demands (Abeloye et al., 2019). Such reservoirs are relied upon to balance rainfall variability and associated drought events and to augment groundwater supply to meet water supply demand with some degree of reliability (Abeloye et al., 2019). In such arid regions runoff of the seasonal stream is affected by impoundment; and the impounded runoff index (defined as ratio of the reservoir capacity divided by average annual runoff), is higher than the rates in humid climate zones (Kondolf and Batalla, 2005). Since 2003, the Khor Arbaat dam storage is undergoing continuous reduction due to rapid sedimentation accumulating in the floor of the reservoir. Notwithstanding the continuous reduction of the dam's storage capacity and reduction of runoff downstream, the dam has contributed to groundwater recharge of shallow groundwater sources and to the sustainability of agricultural activities in the vicinity of the dam (Ali et al., 2013).

This paper assesses the hydrological and environmental impact of the dam in the Khor Arbaat catchment area based on collection of secondary data from available studies and primary data collected from field visits in 2013 and 2014.

METHODOLOGY

Collation and analysis of physical and environmental data

Secondary data from different sources that describe the physical setting, geology, water resources and water supply in the catchment area were collected and assessed. The assessment also included a review of specific documents that describe and discuss the hydrological effects of small dams, water harvesting structures and ponds on recharging groundwater, especially in arid regions. Particular reports and articles that describe the hydrology of Khor Arbaat are cited earlier, while other relevant studies that describe induced groundwater recharge by dams include, but are not limited to ALdrewish (2010), Missimer et al. (2015), Abdalla and Al-Rawahi (2013), Djuma et al. (2017), Ali et al. (2017), and Martín-Rosales et al. (2007). These studies discuss the viability of dams in inducing groundwater recharge in arid regions using analytical and numerical methods. They emphasize that the effectiveness of Wadi (small) dams for recharging alluvium aquifers is controlled by the geology of the site, the thickness and hydraulic conductivity of the alluvium aquifer(s), the hydrological gradient and the reservoir's storage capacity.

Location, extent and environmental setting of the area

The boundary of the Khor Arbaat catchment area was determined using a Digital Elevation Model (DEM) as shown in Figure 1. The Khor Arbaat dam is located at 40 km northwest of Port Sudan City and at 3.2 km upstream of a 30 m-wide narrow gorge (known as the upper gate) located on the lower part of the Khor Arbaat catchment area. The catchment area is 4,201 km^2, extending about 120 km in a southwesterly direction from the dam and from there in a northeasterly direction down to the delta area at the Red Sea front. The catchment area is composed of basement rocks and can be morphologically divided into three distinctive parts (Ali et al., 2013).

(i) The upper mountainous part incised by narrow channels - forming the upstream area of the Khor Arbaat catchment area and extending more than 30 km southwest of the dam.
(ii) The down/lower stream part, starting from the upper gorge (gate) beyond which the Khor Arbaat opens into an alluvial plain of variable width which extends for 12 km down to the Red Sea shore.
(iii) The delta of Khor Arbaat where the local people practice agriculture.

The general geology and structural setting of the Arbaat area was studied by a number of researchers and organizations including Hussein (1975), Lutfi (1975), Musa (1989), and HydroNova (2018). The area surrounding the dam is composed of two huge granitic rocks, intruded into the older metamorphic rocks. Recent unconsolidated deposits of variable thickness (10-35 m) – made of boulders, pebbles, sand and silt – fill the drainage channel of Khor Arbaat, which is structurally controlled by an east–west set of joints and fractures.

Climatically, the Khor Arbaat catchment area is a typical dry zone with a maximum temperature of about 40°C during June to August and a minimum temperature of about 26°C during January and February. The average evaporation during the year is 11.3 mm/day, while minimum and maximum rates are 8.2 and 17.1 mm/day in October and July, respectively. The area is characterized by summer and winter rains from July to October and from December to February, respectively. A thirty-year climatic average (1956 - 1987) indicates an average rainfall of 111 mm per year, while 1976 to 2007 records indicate an average rainfall of 85 mm/year compared to an average of 75 mm/year for the last 10 years (2010-2920). This indicates a decreasing rainfall trend in the area. The probability of rain failure (not receiving rainfall) amounts to 50% and the coefficient of variability (C_v) is about 80% (Ali et al., 2013).

Surface water (runoff) analysis

Though low and highly variable rainfall characterizes the Khor Arbaat catchment area**,** the steep mountainous highlands of the catchment area, which are bare and sparsely vegetated, facilitate the generation of voluminous runoff which commences in the western highlands during August to October. This runoff passes

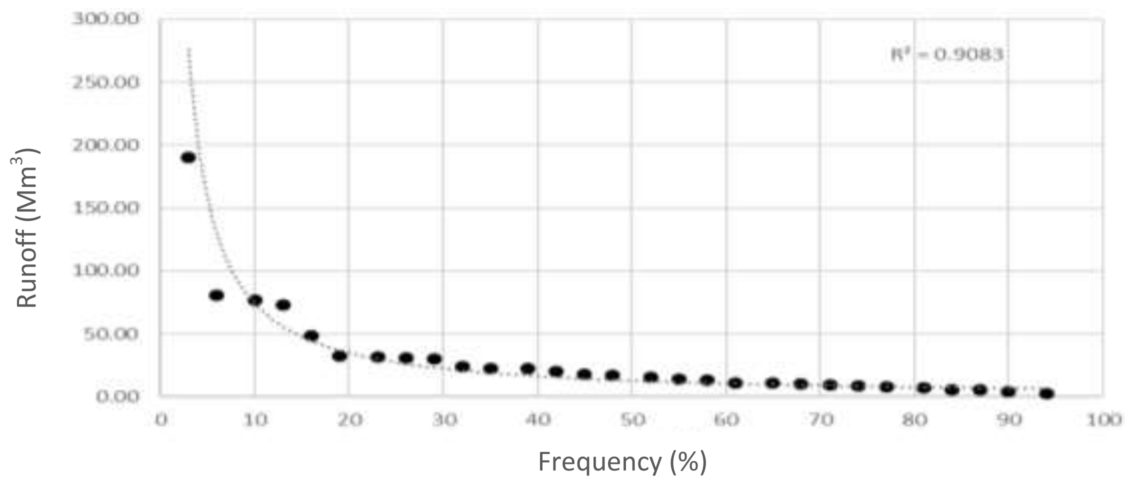

Figure 2. Frequency of runoff, the Khor Arbaat catchment area, Sudan.

through the upper gate, the lower gate, the flood plain, and ultimately discharges into the deltaic area which truncates on the Red Sea. Available data (1959-1986) suggest an average annual discharge of 28.0 Mm^3 including an exceptionally anomalous high value of 190 Mm^3 observed in 1987. On the other hand, Mott McDonald (2016) and Ali et al. (2013) give an average runoff of 18.5 Mm^3, with a low value of 3.8 Mm^3 recorded in 1959/1960 and no (zero) flow in 2011 and 2012. As shown in the calculated annual runoff frequency curve (Kimball, 1960), the average (28.0 Mm^3) and median (15.0 Mm^3) frequencies are 28 and 50%, respectively (Figure 2). This means annual average runoff events could occur 3 times in 10 years. On the other hand, annual runoff as much as 190 Mm^3 could occur twice in 100 years and runoff as low as 5.4 Mm3/year could occur 8 times in 10 years (80% frequency). Despite its low frequency of occurrence, this high value of runoff (190 Mm^3/year) implies that the catchment area could generate higher runoff than the values measured by the gauge station at the upper gate of Khor Arbaat. In fact, the gauge station which was constructed in the late nineteen fifties, needs calibration and rehabilitation due to the physical and morphological changes of the Khor Arbaat channel.

Groundwater and well inventory

Field visits in 2013 and 2014 were conducted in the Khor Arbaat catchment area covering the downstream and upstream parts both east and west of the dam. The purpose of the survey was to collect pertinent groundwater data including water levels, drawdown values, well discharges, size of irrigated plots, and depth of the wells. The survey also included interviews with farmers to solicit their views/perceptions on the dam and to collect historical records on functionality and behavior (fluctuation) of the water levels in the wells. The surveys were confined to three well fields both upstream and downstream of the dam where groundwater occurs in thin alluvium aquifers composed of heterogeneous coarse-grained materials of gravel and boulders.

Tatala well field (a group of water wells) is composed of 7 hand dug wells on the right bank of the Khor Arbaat and about 0.5 to 1.0 km southwest (upstream) of the dam. All wells are shallow, ranging in depth from 4 to 9 m, tapping basement rocks and lined with concrete blocks. The static water level during the time of the survey (December 2013) ranged between 2 and 3 m (below ground level), while during the dry months (March to July 2014) the static water level ranged between 3 and 4 m. However, in most of the wells the depth to the water level was about 3.5 m. Well discharge rate ranged from 7.5 to 20 m^3/h, decreasing during the dry months.

The *Hargvneab* well field is on the right bank of Khor Arbaat, about 5 km west (upstream) of the dam reservoir. It is composed of five irrigation wells dug manually to 6 m below ground level through an alluvium aquifer composed of coarse-grained heterogonous materials. Here, the wells are of relatively low yield (7 to 15 m^3/h) with a total drawdown during the dry months varying from 1.0 to 3.0 m.

The *Arbaat lower gate* well field is about 1 - 2 km east (downstream) of the dam and extends beyond the lower gate with a longitudinal length of 10 km, covering an area of 12 km^2. It is part of the main aquifer, which stores an appreciable volume of groundwater. The thickness of the sediment in the area ranges from 8.0 m in the vicinity of the lower gate to 30.0 m downstream of the lower gate. Generally, the depth to groundwater sources varied from 5 to 7 m during the wet season, while during the dry months (in 2014) it dropped by a further 1 to 2.5 m in the hand dug wells (Table 2). Apart from the hand dug wells used for irrigation, water from this portion of the aquifer is pumped from deep boreholes to Port Sudan City for domestic water supply uses.

Estimation of sedimentation and storage variance

Notwithstanding other factors such as evaporation losses and outflow, the dam's reservoir storage changes and decreases due to the continuous accumulation of silt (sedimentation) on the reservoir floor. Sedimentation results from transportation and deposition of eroded soil in the upstream section of the catchment area. The movement and transportation of sediment is controlled and influenced by many factors, including vegetation cover, topographical slope, runoff volume and size of the eroded particles (Ahmed and Ismail, 2008). The two main mechanisms of transportation and deposition of eroded soil particles are suspension action and gravity action on the sediment-laden water, which enters the bottom of the reservoir in the form of turbidity current (Jaroots, 2009). Due to erosional processes and sparse vegetation cover, Khor Arbaat brings a comparatively large sedimentation load when flood events occur. Before construction of the dam the majority of the sediment load was transported downstream and deposited at the deltaic area on the Red Sea coast.

Table 2. Irrigated areas, specific well yield, maximum and allowable drawdown of the wells in the vicinity of the Khor Arbaat dam, Sudan.

Well field and distance from the dam	Location of the wells		Farm area × (feddan)	Irrigated area (feddans)	Max draw-down (m)	Well yield (m^3/h)	Well specific yield (m^3/h/m)	Allowable draw-down (m)
	Longitude (degree) E.	Latitude (degree) N.						
0.5-1.0 km west of the dam	36.9268	19.8040	6	6	3	15	5	2
	36.9271	191526	5	3	0.5	7.5	15	0.5
	36.9233	19.8052	5	3	1	20	20	3
	36.9219	19.6027	4	3	1	15	15	4
	36.9226	19.8031	5	4	1	7.5	7.5	0.0
	36.9199	19.8023	10	10	2	9	4.5	0.0
	36.6616	19.4644	5	5	0.5	10	20	5.5
5 km west of the dam	36.6471	19.4611	6	6	1	15	15	3
	36.6316	194690	6	3	1	15	15	1
	36.5846	19.1024	6	5	1	14	14	3
	36.7884	19.4950	8	3.5	3	20	7	1.5
1.2 km east of the dam	37.0405	19.8089	8	4	2.5	2.5	1	2
	37.0400	19.8103	16	15	1	15	15	2
	37.0368	19.8109	9	8	1.5	15	10	2.5
	37.0356	19.8107	7	6	1.5	20	13	2.5

*(One feddan = 4200 m^2).

Methods for estimation of reservoir capacity loss due to sedimentation processes differ greatly in terms of their complexity and computation requirement (Garg and Jothiprakash, 2018). A number of studies (Rahmani et al., 2018; Ahmed and Ismail 2008; Akode and Fadallabi, 1994) relate siltation or sedimentation rate to the storage volume related to runoff. Though the relation between storage and sediment volumes is non-linear (Ahmed and Ismail 2008) the following empirical relation is adopted and used in this study to estimate the storage reduction and conversely the sediment load at time (t) interval in the Khor Arbaat dam.

$$Q_s = Q_0(1-r)^n \quad (1)$$

where Q_s is the storage (Mm^3) at time (t), Q_0 is the initial dam storage (Mm^3), r is the annual sedimentation rate (percent) of the storage at time (t), and n is the time (years) since construction of the dam. HydroNova (2018) indicates an annual sedimentation rate of 0.8 Mm^3 accumulated on the floor of the reservoir, while Akode and Fadallabi (1994) indicate sediment deposition thickness of one meter annually as a result of the impoundment whereby runoff is harvested by an earth embankment to recharge the alluvium aquifer downstream of Khor Arbaat. Using the result of the bathymetric survey (by the Ministry of Irrigation and Water Resources, Sudan), which showed dam storage of 8.3 Mm^3 in 2013 (n = 11 years), the annual sedimentation rate (r) can be calculated as 6% of the dam storage (Mm^3) at time (n = 11 years). On the other hand, Abdallah and Stamm (2012) and Ahmed and Ismail (2008) relate sedimentation rate to the reservoir storage volume by the following empirical formula:

$$Q_s = aQ^m \quad (2)$$

where Q_s (Mm^3) is suspended sediment, Q (m^3/s) is inflow discharge, *(a)* and (m) are functions characterizing weight of the annual sediments inflow. Slope of the plot log (Qs) against log (Q) gives (m) and interception at (x = 0) gives (a). Though the equation is simple, it requires a periodic bathymetric survey which limits its usability.

RESULTS AND DISCUSSION

The hydro-environmental impact of the dam can be discussed using the following variables:

(i) Impact on surface water runoff;
(ii) Impact on the base-flow;
(iii) Impact on recharge of groundwater in the vicinity of the dam;
(iv) Impact on dam storage capacity from sedimentation; and
(v) Impact on irrigated land.

Impact of the dam on surface water flow

The dam was built in 2003 with a design capacity of 16 Mm^3 which is about the median annual flow of the Khor Arbaat. However, due to the accumulation of silt, the current (2021) capacity of the dam is about 5.0 Mm^3, which represents less than 33% of the dam's initial storage capacity and the median annual flow of the Khor Arbaat. In normal years (before dam construction), surface water would run down and recharge groundwater resources downstream (lower gate) and in the deltaic area. Since 2003 the dam intercepts annual runoff hence

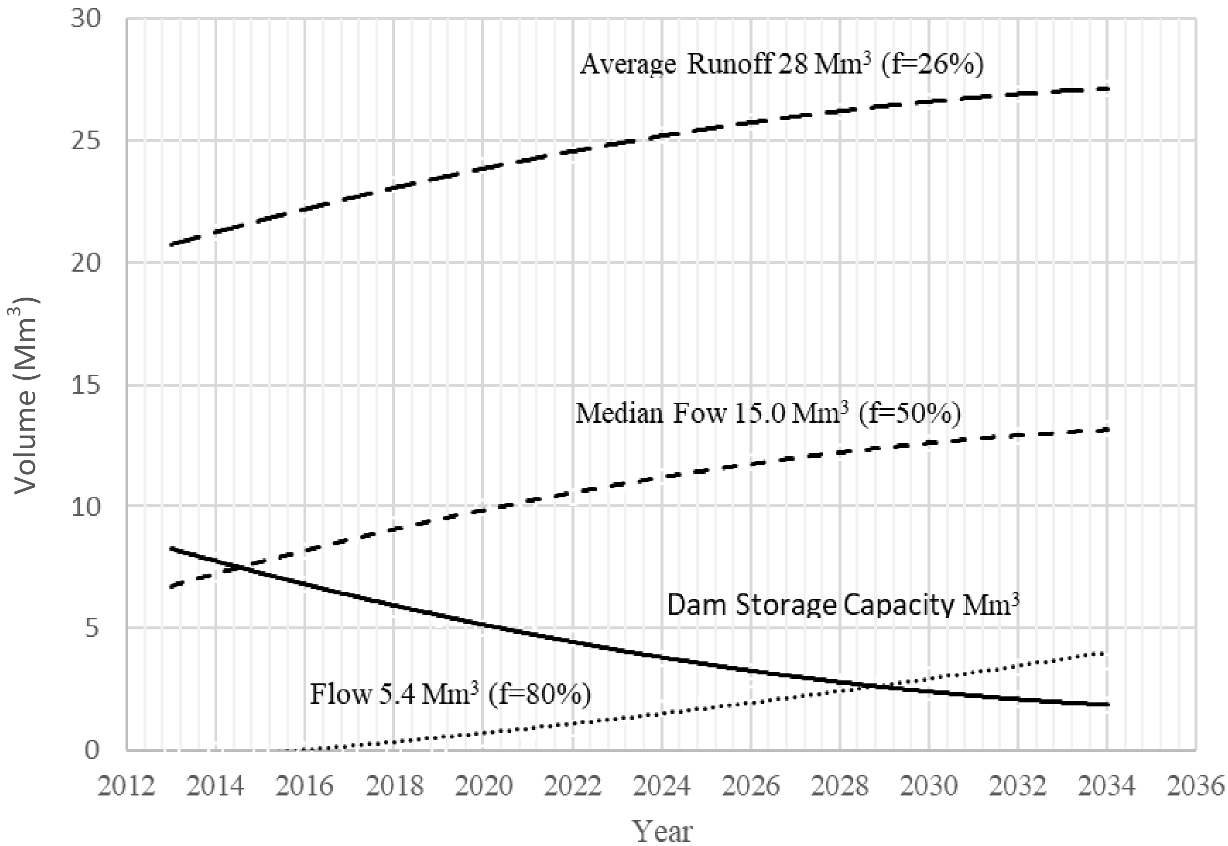

Figure 3. Intercepted runoff by the Khor Arbaat dam (Sudan) and resultant runoff that could flow downstream. With the continuous reduction of the dam storage over time, runoff to the downstream area would increase.

reducing the amount reaching the alluvium aquifer and downstream discharge into the delta (notwithstanding the amount of runoff resulting from local rainfall beyond the upper gate). This has created a pronounced negative impact due to groundwater recession and dryness of open wells used for agricultural production by local farmers in the deltaic area. Dryness of the wells has affected the livelihoods of farmers, inducing the adoption of other livelihoods options, such as migration to Port Sudan City, cutting of trees for fire wood and charcoal production and/or working as daily labor (Mohammed, 2013). As the dam's storage capacity continued to decline due to siltation, the volume of water flowing downstream from the dam increased annually relative to the overall runoff generated upstream in the catchment area. Annual average runoff with a constant frequency (26%), median runoff (5 out 10 years) and runoff of 5.4 Mm^3 (8 out of 10 years) that could flow out of the dam beyond the high and lower gates and possibly down to the delta, are plotted versus continuous reduction of the reservoir storage as shown in Figure 3. Without immediate interventions (such as desilting), beyond 2030 the dam will intercept only about 2.0 Mm^3 of the inflowing runoff.

Impact on the storage capacity of the dam from sedimentation

As mentioned earlier, Khor Arbaat annually receives a large amount of sediment after flood events. Historically, most of the sediment load was deposited at the deltaic area downstream where agricultural activities were practiced utilizing groundwater from shallow dug wells. After construction of the dam large loads of sediment are trapped by the dam. The amounts and rate of sediment deposition on the floor of the reservoir are a result of overall degradation of the Khor Arbaat catchment area. The lack of proper land use management in the upper reaches of the catchment area could be the main reason for accelerated soil erosion. A number of additional factors affect sediment transportation and deposition. These include the size of the sediment particles as well as their settling velocity and specific gravity; the geology, soil type, topography (including vegetation cover) and morphology of the catchment, the rain and runoff intensities and capacity of the channel (Osman, 2015). Though no particles sieve analysis was conducted, according to Taha (2020) the deposited sediment on the floor of the reservoir is cohesive as it is composed of silt

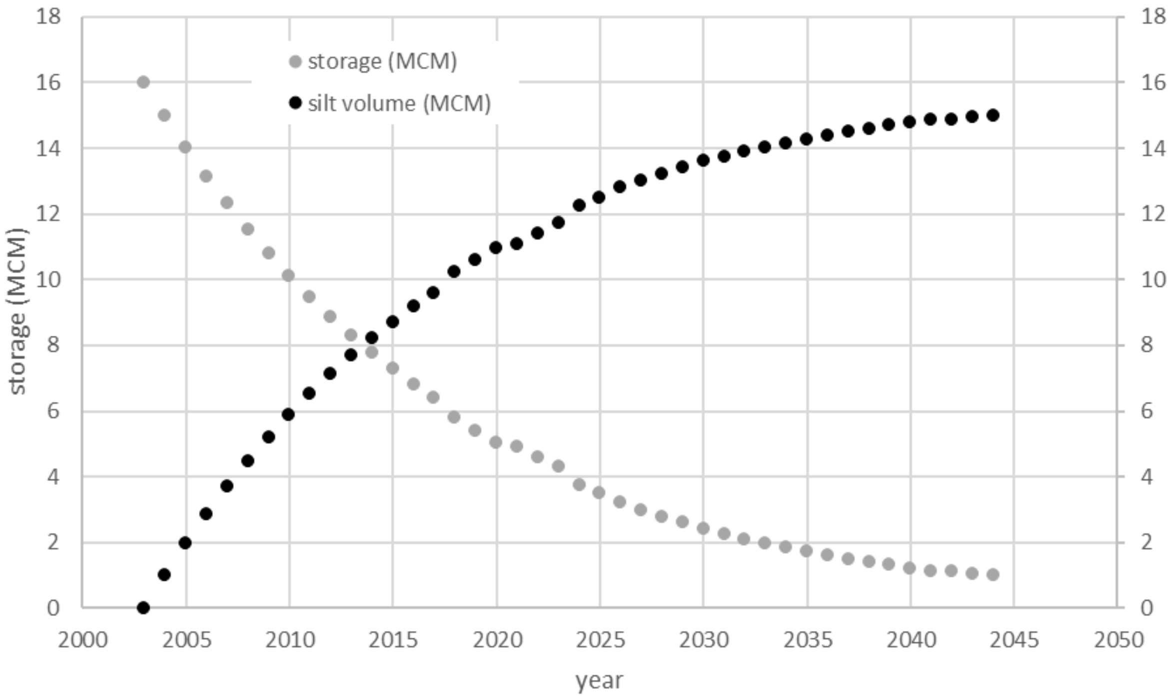

Figure 4. Reduction of the Khor Arbaat dam **(Sudan)** storage capacity and accumulation of silt with time.

and clay of grain size less than 0.063 mm (Osman, 2015). Accordingly, the various characteristics of the Khor Arbaat catchment area contribute to the high sedimentation rate in the reservoir and continuously reducing its storage capacity.

As shown in Figure 4 in 11 years (up to 2013), the reservoir lost almost 50% of its storage capacity, and the dam is projected to be 94% silted up by 2044 (in 23 years from 2021). It is important to note that the sedimentation deposition rate is non-linear and inversely correlates with the decrease of the storage capacity of the reservoir (Figure 4). HydroNova (2018) indicates an average annual sedimentation rate of 0.80 Mm^3 while Akode and Fadallabi (1994) indicate sediment deposition thickness of 1 m annually by water harvesting infrastructure constructed to recharge the alluvium aquifer downstream of the Khor Arbaat. In this study an annual sedimentation rate of 6% of the reservoir storage capacity at time (t) interval was used to estimate the storage reduction resulting from sedimentation. Though the value (6%) is comparable with 0.8 Mm^3 (5%) sedimentation rate as stated by HydroNova (2018), this rate is high by general standards. Globally, Ali and Shakir (2018) quote an annual loss of 0.5 to 1% of reservoir storage due to siltation as generally acceptable.

Sedimentation and evaporation reduce the Khor Arbaat dam's storage, which currently and in future will directly impact the city's water supply services. In arid regions net evaporation (evaporation – rainfall in a location) accounts for at least 40% of the available reservoir storage (Mady et al., 2020) as compared to 29% in semi-arid regions (Abeloye et al., 2019). With due consideration to evaporation loss, at present (2021) only 8,219 m^3/day (3.0 Mm^3/year) is available from the dam for the city's domestic water use, depending on the amount of runoff and its frequency of occurrence (Figure 3). To reduce the effect of evaporation losses and maximize the benefit from the available reservoir storage, pumping from the dam should be maximized during October to March when evaporation is comparatively low (about 8.2 mm/day) and when reservoir storage can be replenished by winter rainfall/runoff, particularly during October and November. This means the pumping rate from the dam can be doubled in 6 months (rather than sustained throughout the 12 months of operation) while pumping from the alluvium aquifer can be maximized during the other months of the year (April to September).

On the other hand, the reliability of the projected siltation rate and reduction of the Khor Arbaat dam's storage is affected by the extent of climate change, particularly changes in rainfall, runoff and temperature in the area. Studies in this respect (Sara et al., 2018; USAID, 2016) predict a temperature rise of 0.5 to 3°C by 2050, particularly in the Red Sea area, Sudan. The studies also predict a change from 83 to 77 mm/year in the average rainfall and an increase from 252 to 283 mm/year in the maximum rainfall while its minimum value remains the same during the period from 2017 to 2100. Such changes in rainfall patterns combined with the temperature rise, intensify both drought and flood events

Table 3. Variation of groundwater levels with respect to distance from the Khor Arbaat dam, Sudan.

Well field	Distance from the dam (km)	Water level (m below ground)	Change in groundwater level (m) after construction of the dam*
West of the dam	0.5 -1	3.0	(+) 1.5
Upper gate west of the dam	5.0	4.0 -5.0	(-)1.0 - (-) 2.0
East of the dam	1.0 -5.0	6.0 – 7.0	(-) 4.0 - (-)6

(+)/(-) = Water level rise/drop.

in the Khor Arbaat catchment area, though the probability of drought is higher than flood events. The decrease in the average rainfall pattern and the rise in temperature reduce the generated volume of runoff in the Khor Arbaat catchment area. And at the same time these climate change factors increase soil erosion and desertification in the catchment area and consequently increase the sediment load in the water entering the dam.

Besides reducing the reservoir storage, siltation has also resulted in the blockage of the dam outlet. As a result, the water from the reservoir is siphoned using polyethylene pipes. The accumulation of sediment also has caused head dropping from 22 m (231 - 209 masl) to 12 m, and 9 m in 2003, 2013 and 2018, respectively (HydroNova, 2018).

Entrapment of silt by the dam has negatively affected agricultural activities downstream in the delta due to a decrease in land fertility (Mohammed, 2013). Deposition of sediment on the floor of reservoir also has other economic impacts such as the need for de-silting (dredging) and the high costs this would incur. In the Gezira Scheme (Sudan) for example, the cost of de-silting is USD 0.634 million for the removal of one million m^3 of sediment (Osman, 2015). For the Khor Arbaat reservoir, HydroNova (2018) estimates USD 2.2 million would be required to de-silt up to 50% of the reservoir's capacity and to restore annual storage to about 7.0 Mm^3. On the other hand, concentration of the suspended materials in the raw transported water from the dam reservoir may increase deposition of silt inside the pipes, thus reducing their water conveyance efficiency. Accumulation of silt in the reservoir may also cause change in water quality. Taha (2020) indicated biological contamination and high concentration (60-64%) of iron oxide in water samples retrieved from the dam in 2019. The samples failed to meet the Sudanese and WHO drinking water quality standards.

Impact on the base-flow

Groundwater flow in Khor Arbaat originates from the upper reaches of the catchment area west of the dam. The presence of surface joints and fractures assists in the collection and convergence of appreciable volumes of surface runoff, which travels downwards as subsurface groundwater flow facilitated by the high hydraulic gradient along the Khor. Due to the shallowness and narrowness of the channel at the upper gate east of the dam, groundwater can pass through the upper gate with a high velocity, intersecting with the ground surface and ultimately appearing on the surface as a base-flow, which could contribute to the recharge of the aquifer. Prior to the construction of the dam the average base-flow was 9,831 m^3/day during the period 1956-1992 and 12,950 m^3/day in 2000 (Ali et al., 2013). After construction of the dam, and during the 11 years of the dam's operation (from 2003 to 2014; the year in which the study was conducted), the base-flow dropped to 4,320 m^3/day. Probably this amount of the base-flow results from the groundwater flow into the 3.0 km - length of the aquifer portion between the dam and the upper gate where groundwater appears as a base-flow.

Impact on groundwater recharge in the vicinity of the dam

The dam's contribution to shallow aquifer recharge was considered by analyzing: (1) groundwater levels in the wells, (2) allowable/permissible drawdowns in the wells; and (3) groundwater levels in the wells before and after construction of the dam taking into consideration the distance of the well fields from the dam. As shown in Table 3, wells less than 1 km west (upstream) of the dam displayed shallower water levels at an average of 3.0 m below ground level, while comparatively deeper groundwater levels of about 4.0 to 5.0 m below ground level were observed at wells about 5 km west (upstream) of the dam. On the one hand, this (small) variation between the measured water levels in the two well fields upstream of the dam reflects the effectiveness of the dam in recharging wells relative to their respective proximities from the reservoir of the dam (Table 3). On the other hand, though some wells are located about 1 km downstream (east) of the dam, they showed deep water levels (up to 7 m). This part of the aquifer east of the dam seemed to receive recharge through groundwater seepage and base flows before construction of the dam. This seems to have been cut off after construction of the dam and accumulation of fine-grained sediment on the floor of the reservoir, which ultimately reduces the

Table 4. Available arable and additional lands to be irrigated based on the total allowable drawdown in the wells in the vicinity of the Khor Arbaat dam, Sudan.

Well field	Available land (feddans)	Irrigated area (feddans)	Cultivated/ available land (%)	Average drawdown (m)	Irrigated area/1 m drawdown (feddans)	Total allowable drawdown in the field (m)	Additional area be irrigated (feddans)
1 km west of dam	40	34	85%	1.8	2.8	15.0	5.0
5 km west of the dam	53	25	47%	1.5	2.4	8.5	20.0
1 - 5 km east of the dam	60	33	55%	1.6	3.5	9.0	30
Total	213	112	53%	1.7	2.7		55.0

downward recharge beneath the dam. Probably the only source of recharge at present is localized surface water runoff, which percolates through the north-south joints and fractures into this portion of the aquifer. Table 3 also shows water level changes after construction of the dam. Water level in the well field less than 1 km west (upstream) of the dam showed a raise of up to 2 m compared to pre-construction of the dam. Groundwater level at a distance of 5 km west (upstream) of the dam showed a drop of up to 1.8 m (-1.8 m) after construction of the dam. On the other hand, wells east (downstream) of the dam received appreciable groundwater recharge from Khor runoff, groundwater underflow and base flow before construction of the dam. After construction of the dam, the structure intercepts runoff and cuts off the base flow/underflow, with no appreciable recharge seeming to reach this area. This is reflected by a drop of up to 6.0 to 7.0 m in groundwater levels observed in various hand dug wells, despite being at a short distance of 1 km east (upstream) of the dam.

Impact on irrigated land

According to Mohammed (2013) after construction of the dam and due to water submergence, the cropped land immediately west of the dam was reduced by 24.2 feddans (one feddan is 4200 m^2) and the population of the palm trees was reduced by 73%. In additional to domestic supply, water in Khor Arbaat is used to cultivate staple crops and vegetables in small areas irrigated by the open wells in the vicinity of the dam. Based on results from representative samples of well clusters (about 50% of the total number of wells in the area), irrigated areas constituted about 53% (195 feddans) of the available arable land in 2013 as shown in Table 4. In the area near the dam, about 85% of the available arable land was irrigated, possibly due to the high groundwater potential enhanced by the recharge from the dam. While further away, about 5 km upstream of the dam only 33% of the available arable land was irrigated. Notwithstanding other factors the drop of water level is a function of the volume of the pumped water and the extent of the area under irrigation (that is, the irrigated acreage). As shown in Table 4, irrigation of 2.4 to 3.5 feddans could cause a drop of 1 m in the water level in pumped wells. However, this statement should be taken with caution since the relationship between irrigated (cultivated) area versus drop in water level or drawdown is non-linear given there are other factors that can interplay and determine the size of the irrigated area (Figure 5). The potential of expansion of irrigated lands in the area was judged by the value of permissible drawdown in the wells (measured as: total depth of the well minus water level in the well). The allowable (additional) area that could be added was calculated as an area irrigated by 1 m of water drop in the well (drawdown) multiplied by the total permissible drawdown in the well field. These results are shown in Table 4. In the well field (a group of wells) at 1 km upstream of the dam, though it maintained higher allowable drawdown, only 5 feddans could be added as about 85% of the lands were already under cultivation. While 5 km west (upstream) of the dam, 20 feddans of the available uncultivated lands could be added; and east of the dam, on the other hand, 30 additional feddans could be cultivated, but with due consideration to the wells' sustainable yield and replenishment (recharge).

Conclusion

Though the Khor Arbaat dam has provided additional recharge to the nearby upstream well fields, long term sustainability of this recharge and functionality of the shallow wells can be in jeopardy due to the current and continuous sedimentation of the dam and the area's vulnerability to, and high incidence of rainfall failures. In the short term, the present level of agriculture activities could be sustained only in the areas 1 km upstream (west) of the dam. Wells east (downstream) of the dam that used to receive recharge by under and base-flows from the upstream have been deprived and cut off from this recharge supply due to construction of the dam. However, the continuous reduction of the reservoir's storage capacity due to sedimentation means the amount of annual runoff that could contribute to recharging the

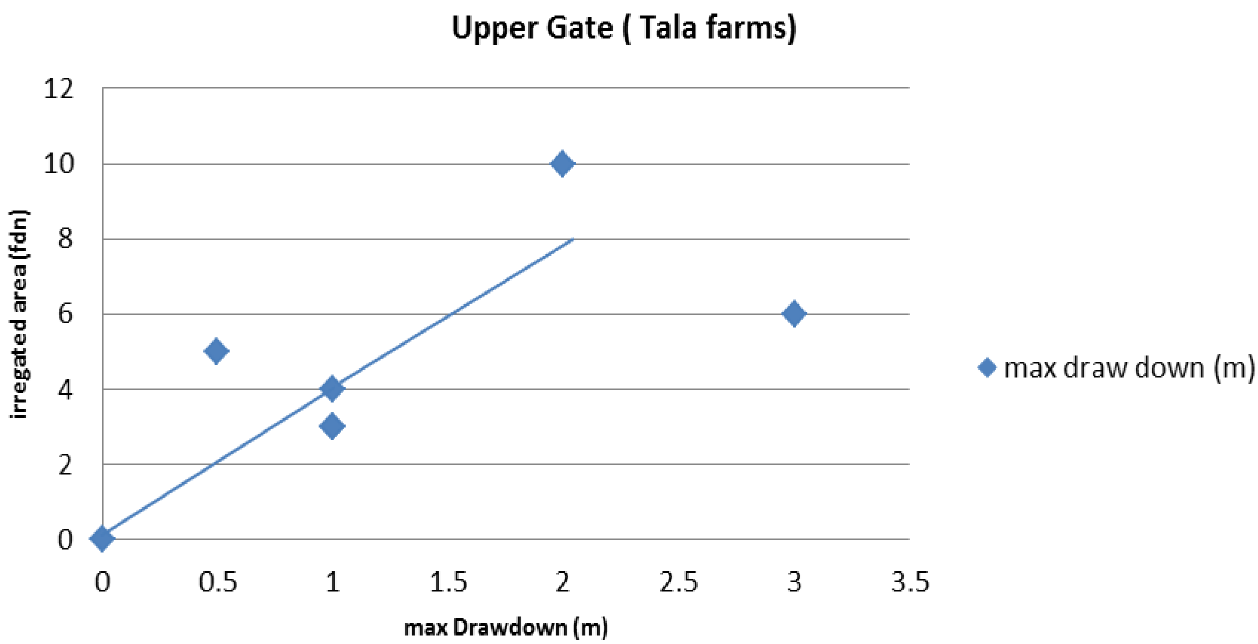

Figure 5. Poor relation/correlation between cultivated area (feddans) and maximum drawdown (drop) in water level in the wells 1 km upstream of the Khor Arbaat dam, Sudan.

alluvium aquifer downstream would increase.

In the short term, deepening the irrigation wells to tap into the fractured aquifer can increase groundwater yield from these wells. This can be done using percussion and/or hammer drilling rigs. Also, adopting irrigation efficient technologies such as drip and/or piped irrigation methods, and lining the irrigation canals to reduce seepage, would improve the efficiency of irrigation water use (with an accompanying enhancement in production). To reduce water losses due to evaporation, it is advisable to maximize pumping from the dam during the winter months (October to January) when the evaporation rate is relatively low, while pumping from the alluvium aquifer can be maximized during the dry months.

In the longer-term, planning, use and management of water resources and water facilities, including the dam and water wells in the Khor Arbaat catchment area, should be viewed and considered within an overall context of Integrated Water Resources Management (IWRM). Applying the principles of IWRM, the whole Khor Arbaat catchment area (up and downstream) should be considered during decision-making and its water resources linked with other natural resources, livelihoods and local social activities. IWRM also requires considering the whole catchment area in terms of proper monitoring and assessment of surface and groundwater resources, promotion of conjunctive water use, and integrating water and land use management. Collectively, such interventions can reduce the rate of soil erosion and sedimentation potentially introducing water harvesting infrastructure in the area.

CONFLICT OF INTERESTS

The author has not declared any conflict of interests.

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