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A case study of sedimentation problems of Wadi Arbaat's dams reservoirs

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Abstract. The proper management of reservoir sedimentation is of critical importance for the sustainable development of surface water resources. Dams' reservoirs are losing their ability storage due to sedimentation processes worldwide. These losses vary from one reservoir to another depending on the characteristics of the watershed and water streams. Therefore, the performance of reservoirs is incredibly vulnerable. The area surrounding Red Sea State is under arid and semi-arid condition, and immensely suffering from a shortage of safe and reliable drinking water supplies. Wadi Arbaat is the primary source of water supply in Port Sudan city. Valleys mostly surround the Red Sea State and Wadi Arbaat suffer from a severe decline with the steep slope of 6-10 m/km. Therefore, the Wadi carries large quantities of sediments, which deposit in dams' reservoirs during the flood periods. The siltation strongly influences these dams and their reservoirs suffer from serious problems represented by increasing silting level and shortage in storage capacities. Consequently, this study aims to investigate the current situation and problems of the three existing dams and make a proper decision with a comprehensive and specific vision in the future. The main problems caused by reservoir sedimentation in the Red Sea Mountains are described as a reduction in the storage capacities, and entry of sediments into control structures such as sluice gates. The problems are further exacerbated as there is no guidance on the decision supports tool that is needed to underpin silting in the flood period and water resources management in these steep slope areas. The sedimentation processes, problems and changes of dam operation are discussed in this paper.
Keywords: sea port corporation dam; sedimentation; siphon system; sluice gate; upper gate dam; Wadi Arbaat

1. Introduction

Dams and reservoirs are developed by humans to manage with the inconsistency of water supplies a long time. These dams provide numerous advantages for human lives, such as irrigation water, hydropower generation, flood control, recreation, and fishing. To date, the common engineering practice was to design and operate reservoirs to fill with sediment gradually. This makes benefits from storage over a finite period (Palmieri *et al*. 2001, Sumi *et al*. 2004, Jahanbakhti *et al*. 2017, Aldrees 2020). With such an approach, the penalties of sedimentation and project abandonment are left to be taken care by future generations. However, this future has already arrived for several dams, and in some cases earlier than expected (Wang *et al*. 2005, Haregeweyn *et al*. 2006, Najarkolaie *et al*. 2017, Youdeowei *et al*. 2019). The formation of sediment in the dams could create several problems in upstream and downstream and may vary widely from one site to another. A main influence of sedimentation is the loss of storage capacity, which can have a severe effect on water resources development by the reduction of water supply, hydropower production, and irrigation water supply as well as the efficiency of flood control systems (Kothyari 1996, Rãdoane and Radoane 2005, Yun *et al*. 2017, Madhav *et al*. 2018, Isnain and Abd Ghaffar 2020). In the year 2011, UNESCO and International Sediment Initiative (ISI) defined the sediment (alluvium or silt) as comprised of solid particles of mineral and organic material transported by water. In river systems, the quantity of sediment transported is controlled by both the supply of sediment and the transport capacity of the flow. The "suspended sediment load (SSL)" indicates to the fine sediment that is carried in suspension. On the other side, the "sediment bed load (SBL)" includes larger sediment particles that are transported in the bed of the stream by rolling, sliding or saltation. Most rivers and streams will transport sediment in each of these load forms according to the flow situations (Initiative 2011, Singh *et al*. 2019). Approximately 1% of the storage volume of the world's reservoir is lost annually due to sediment deposition (Stevens 2000). All reservoirs formed by constructing dams on natural rivers are subject to some degree of sediment inflow and deposition. Because of the very low velocities in reservoirs, they tend to be very efficient sediment traps. Therefore, the amount of reservoir sedimentation over the life of the dam needs to be predicted. If the sediment inflow is large relative to the reservoir storage capacity, then the useful life of the reservoir may be concise. For example, a small reservoir (Upper Gate Dam) on the Wadi Arbaat near Port Sudan City was filled with sediment during the first years of operation. If the inflowing sediments settle in the reservoir, then the clear water releases may degrade the downstream river channel. The sediment that is constantly supplied and hydraulically carried in channels and streams is provided by

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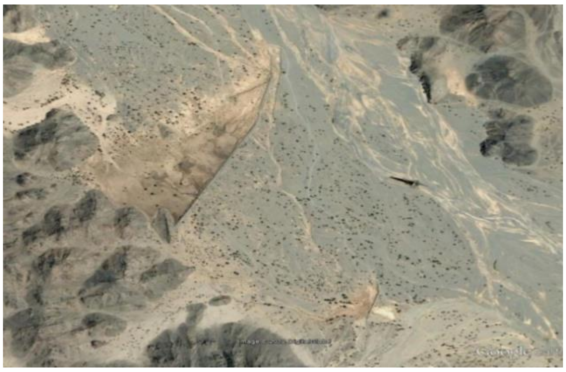


Fig. 1 Khor Arbaat – port Sudan changing the flow direction and velocity

Fig. 2 Surface dam

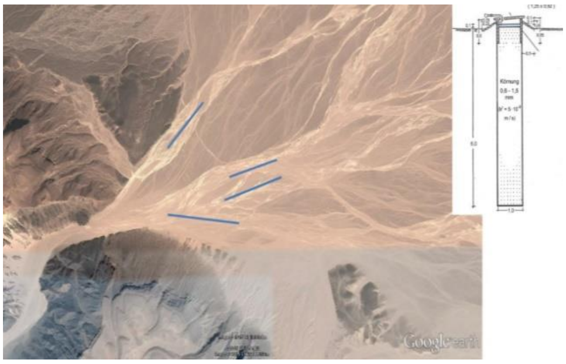


Fig. 3 Infiltration trenches parallel to the stream

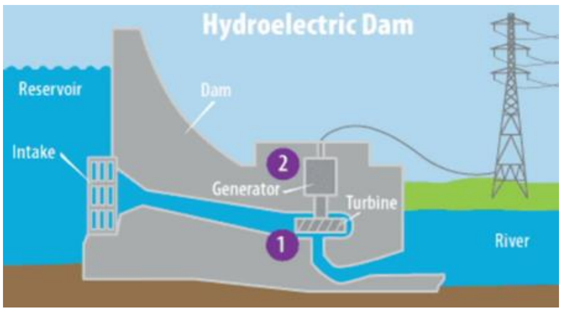


Fig. 4 Hydroelectric dam plot

rainfall, runoff and river channel erosion (Zhang *et al*. 2019). All reservoirs established by constructing dams on natural rivers are subjected to some degree of deposition and Sediment Inflow (SI) (Lane *et al*. 1997). Due to the very low velocity in reservoirs, they have a tendency to be very effective sediment traps. Hence, during the life of the dam, the amount of reservoir sedimentation should be predicted. If the SI is large concerning the capacity of reservoir storage, the effective life of the reservoir may be short. For instance, a small reservoir (upper gate dam) on the Khor Arbaat near Port Sudan city was filled with sediment during the first years of operation. Different prediction techniques have been introduced for estimation and optimization applications. Prediction quality depends on a variety of variables such as error, soft computing approach and available problems (Katebi *et al*. 2019, Trung *et al*. 2019, Safa *et al*. 2020). Artificial Intelligence (AI) methods are proposed to alleviate estimation problems (Chelgani *et al*. 2010, Panda *et al*. 2014). By interlacing with classical optimization algorithms, AI techniques have become essential prediction ways (Miao *et al*. 2018, Sun *et al*. 2018). Classical optimization procedures such as ant colony, bee colony, particle swarm, and firefly algorithms are used to address some short- comings in the way of prediction. The neural network is also employed with AI techniques to enhance the efficiency of the prediction, while the hybrid algorithms were proposed for different types of objective evaluations. Machine learning and deep learning (Qi *et al*. 2020, He *et al*. 2021, Li *et al*. 2021a, b Wu *et al*. 2021) are other types of AI techniques, which are used and developed during estimation purposes. Employing these techniques for prediction, describing runoff volume, debris volume and sediment texture as input instead of output can lead to predicting the different loads (Ebrahimi *et al*. 2017), no matter what kind of loads will be applied. Between the most important leads related to structures, those related to dynamic response of structures are on top (Li *et al*. 2021a, b) and those related to dam like sediment load. Sediment ingredients may consist of different debris such as crushed rocks (Hu *et al*. 2021), sand, marble and other types of probable waste sludge. The mechanical properties of the sediment may be similar to that of specific soils in which most parts of them are sediment. Hence using previous studies data about mechanical properties of muddy soils could be helpful (Miao *et al*. 2019). Fig. 1 shows Khor Arbaat – Port Sudan Changing the flow direction and velocity, Fig. 2 shows the surface dam and Fig. 3 shows Infiltration trenches parallel to the stream.

Fig. 4 shows hydroelectric dam plot, Fig. 5 shows the components of dam are called sedimentation and Fig. 6 shows typical reservoir sediment profile. Fig. 7 illustrates the sedimentation process in a storage reservoir as treated by Sloff (1991, 1997). Moreover, according to Morris and Fan (Stevens 2000), deltas are generally categorized into three main groups. First, Top Set Area, where the top set deposits contain the coarsest fraction of the sediment load, which is rapidly deposited.

Second, Fore Set Area (Delta front), where the forest deposits are characterized by an increase in slope and a decrease in grain size as compared with those of the top set area.

Third, Bottom Set Area (Beyond the foreset slopes), where the bottom set deposits consist of fine sediment, which is deposited beyond the delta by turbidity currents or

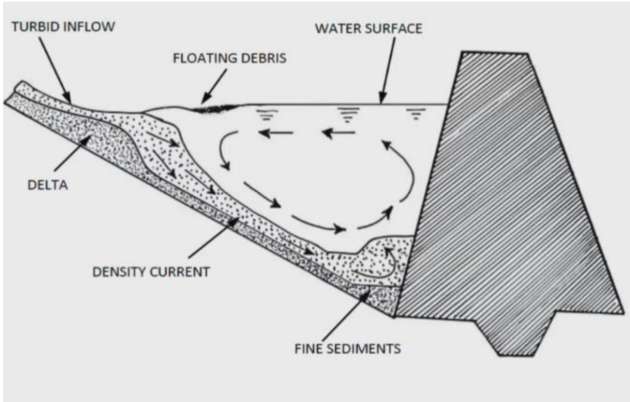


Fig. 5 The components of dam are called sedimentation

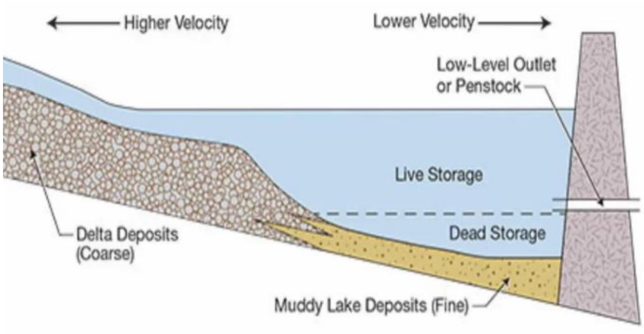


Fig. 6 Typical reservoir sediment profile

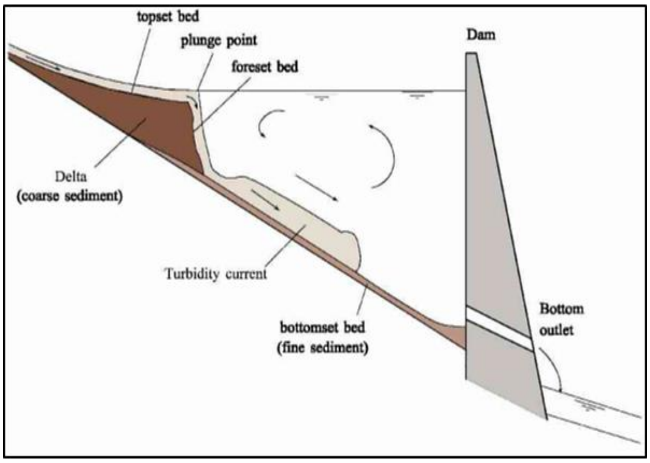


Fig. 7 Schematic presentation of principle sedimentation processes in river-fed storage reservoirs (Sloff 1997)

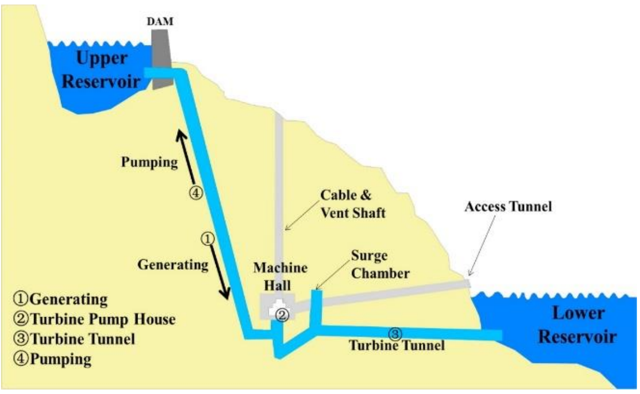


Fig. 8 Typical reservoir sediment profile (Stevens 2000)

non-stratified flow. Besides, Fig. 8 reveals the Typical Reservoir Sediment Profile, in which sedimentation in the reservoir behind a dam takes the form of progressively finer materials being deposited as flows approach the dam (Stevens 2000).

Fig. 9 shows the computer simulation of Wadi Arbaat's Dams Reservoirs, and Fig. 10 shows simulation of Releasing Reservoir Sedimentation within Dam Removal. In some developing countries where watershed management measures are not carried out effectively, reservoir storage is lost at much larger rates (Boroujeni 2012, Wilson *et al*. 2017, Choudhari *et al*. 2018). Small dams' reservoirs are losing their capacities due to sedimentation processes during flood season, and are seriously threatened in their performance. Without any mitigating measures, the viability of many reservoirs worldwide is questionable, as the profits do not balance the impacts and losses. The sedimentation rate of reservoirs depends mainly on the size of the reservoir relative to the amount of the sediment flowing into it. For example, a small reservoir on an extremely muddy river or Khor will rapidly lose capacity; on the contrary, a large reservoir on an obvious river or Khor may take an extended period (up to centuries) to lose an appreciable amount of storage (McCully 1996). According to Morris *et al*. (Garcia 2008), the reservoir's life could be divided into three different stages. (i) Continuous and rapidly occurring sediment accumulation, (ii) Partial sediment balance, where often fine sediments reach a balance, but coarse sediments continue to accumulate, and (iii) Full sediment balance with sediment inflow and outflow equal for all particle sizes. Besides, Shen and Julian (Maidment 1993) stated that the accumulation of Sediment in Reservoirs might have the following effects: Reducing the useful storage volume for water in the reservoir; Changing the water quality near the dam; Increasing the flooding level upstream of the dam because of sediment aggradation; Influencing the stability of the stream downstream; affecting the stream ecology in the dam region; and causing other environmental effects by the changing water quality. To the author's best knowledge, there are no records or any sediment measurements and specific studies were carried out at Wadi Arbaat. However, only two studies have been conducted so far as reservoir sedimentation. One study was conducted by Sudan Water Harvesting Project and SINOHYDRO Bureau, which summarized the survey in reservoirs of the Red Sea State in December 2010. This study was specified concerned about the dams' problems at that time and the resolution. Another study was done by the Ministry of Water Resources and Electricity (Dams Implementation Unit, DIU); work was done for bathymetric-survey for Upper Gate Dam 1 in March 2013 and July 2018. Nevertheless, these studies were only restricted to the assessment of the current situation of the dams, but they did not analyze sediment transport and yield from the watershed. To better quantify the problem, this study presents a brief overview of the Wadi Arbaat (in Eastern Sudan) watershed Characteristics and the impact of the sedimentation on its three dams. This significant problem will affect the water supply to Port Sudan City. Therefore, this paper aims to study and evaluate the sediments occurring in the area surrounding Red Sea State

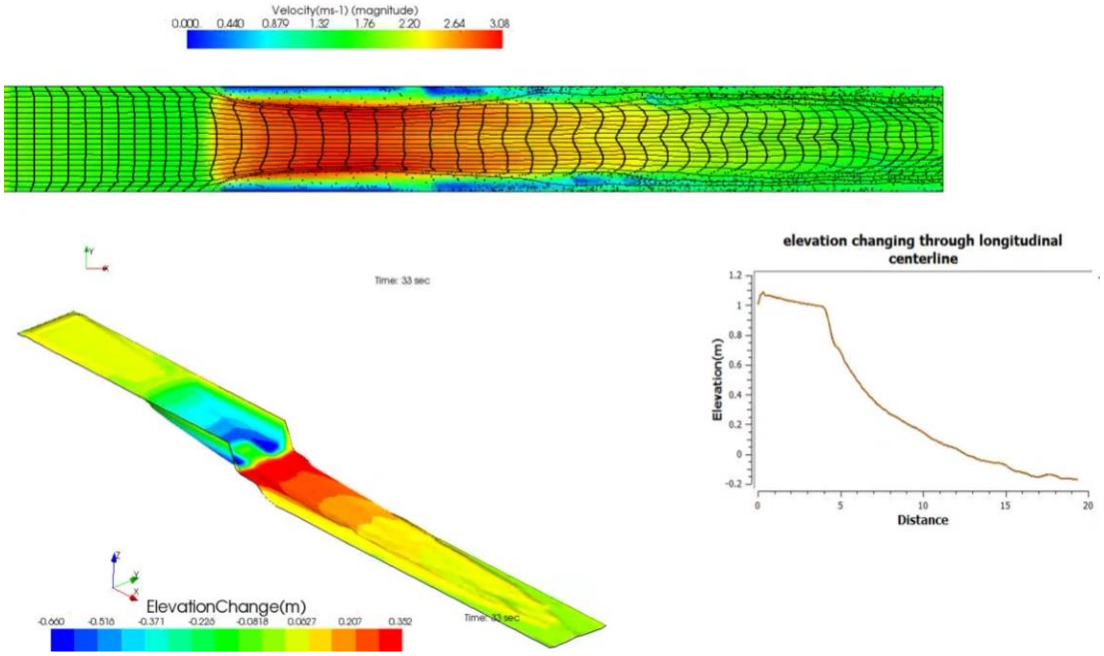


Fig. 9 Computer simulation of in Wadi Arbaat's dams reservoirs

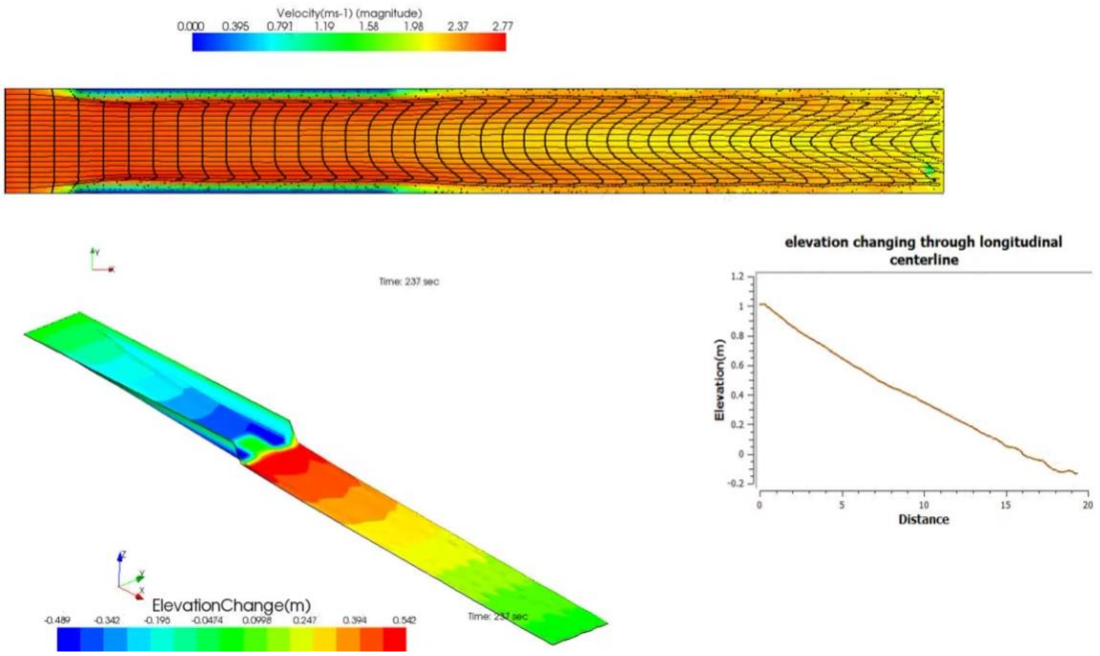


Fig. 10 Simulation of releasing reservoir sedimentation within dam removal

is under the arid and semi-arid condition that carry large amounts of sediments that are trapped in the dams. This study focused on the dams located on the Khor Arbaat as a case study. Another study, proposed appropriate methods to measure and mitigation in order to minimize the sediment accumulation, which finally leads to a decrease in the maintenance and operation costs. Indeed, Watershed streams in arid regions form ephemeral streams that dry up entirely in the rainless period. These streams are called Wadies in Arab Regions. This term is increasingly recognized as an international name used in most hydrologic publication all over the world (Soliman 2010). Also, in Sudan, the Wadi is called Khor such as Khor Arbaat. Fig. 11 shows the heterogeneity of the sediments. Fig. 12 shows the consolidated structure of the Wadi sediments showing that the horizontal and vertical flow may have obstacles due to the change of fine and coarse grains.

2. Research methodology

The methodology used in this study was completed by taking utilizing of previous studies related to recent sedimentation issues in the Wadi Arbaat, despite their

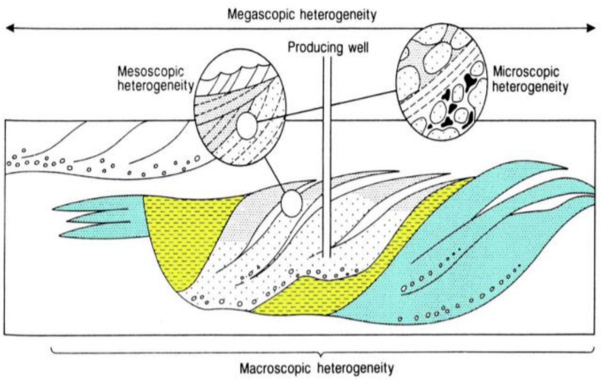


Fig. 11 Heterogeneity of the sediments

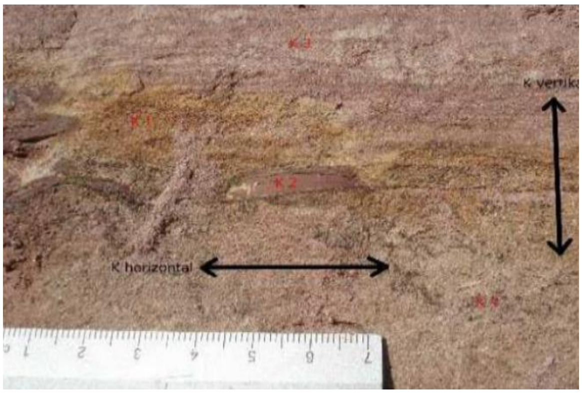


Fig. 12 The consolidated structure of the Wadi sediments shows that the horizontal and vertical flow may have obstacles due to the change of fine and coarse grains

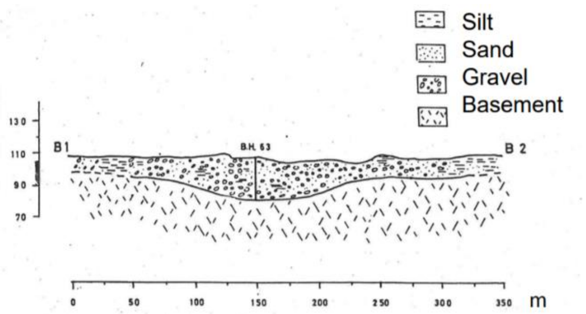


Fig. 13 Cross section of the Wadi

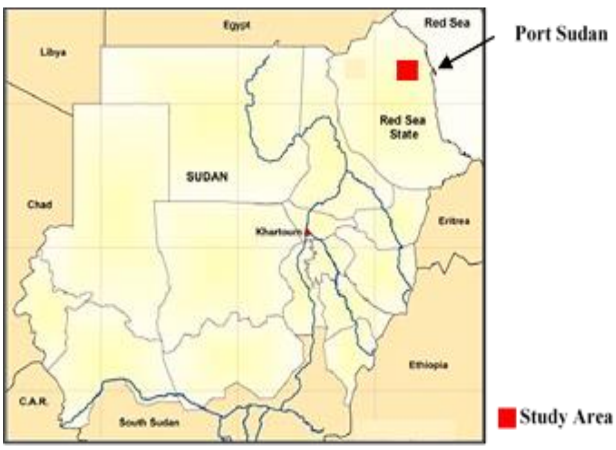


Fig. 14 Location map of study area (Hassan *et al*. 2019)

Table 1 Catchment characteristics of Khor Arbaat

Area (km^2)	Length (km)	Slope (m/km)	Time concentration (hr.)	Total volume ($10^6 m^3$)
4200	160	6 - 7	18	32

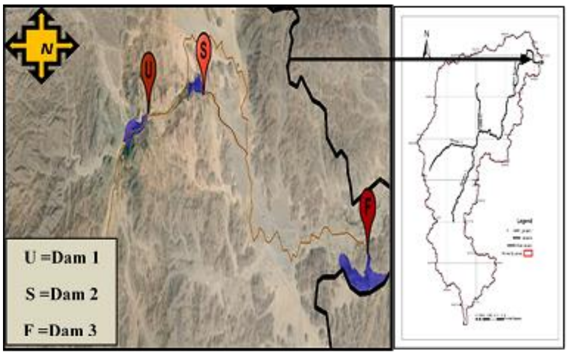


Fig. 15 Dam 1 (F), Dam 2 (S), and Dam 3 (U) locations

scarcity. In addition, summarizing sedimentation issues related to the study of the three dams (Upper Gate Dam 1, Sea Port Corporation Dam 2 and Fourth Reservoir Dam 3), and its impact on the water supply of Port Sudan.

2.1 Hydrology of Wadi Arbaat

Fig. 13 shows Cross section of the Wadi Arbaat. As shown in Fig. 14, Wadi Arbaat Watershed lies in the Middle central of Red Sea State Hilly landscape, and valleys characterize it. Wadi Arbaat drains a catchment area of about 4387 km^2 through the upper gate into an alluvial basin of lower gate. The catchment area of the Wadi is by far the largest in this region. Arbaat is an alluvial basin of 20-30 m thick, and an area of 13 km^2 structurally controlled between the upper and lower gates. The upper gate is controlled by Nakasib and Oko shear zones (Pantuliano 2002). Characteristics of Khor Arbaat's watershed are given in Table 1.

2.2 Description of the case study dams

There are three dams in Wadi Arbaat constructed to supply drinking water in the city of Port Sudan and around rural areas. Three dams, according to their position at the Wadi are Upper Gate Dam 1, Sea Port Corporation Dam 2 and Fourth Reservoirs Dam 3, respectively (Fig. 15). These dams are located between the upper and lower gate areas; because the area's characteristics are suitable for constructing dams. The designed capacities of the dams vary between 16 to 5 Mm^3, but due to the sedimentation problem. This area is located in the mid-low mountainous area at the boundary between east of the Nubian Desert mesa and the Red Sea coastal plain. It is a bedrock mountainous area suffering long-term denudation featured by gentle mountains, round mountaintops, and scattered Wadis developed gullies and seasonal streams.

The overall terrain within the border is characterized by high-west and lower east inclining from west to east, a general elevation of 350-1600, a general relative altitude

Table 2 Inlet and outlet areas of dams

Areas	Coordinates		Elevation (m)	Dams on area	Width (m)
	E	N			
Upper gate	36°56’23.03”	19°50’5.50”	181	SPC Dam 2 Upper Gate Dam 1	30 70
Middle gate	37° 1’7.15”	19°48’15.65”	146	Dam proposal in the future (SINOHYDRO, 2010)	450
Lower gate	37° 2’44.87”	19° 48’22.03”	110	Lower Gate Dam 3	450

Table 3 Data of three dams

Dam	Coordinates		Elevation (m)	Design capacity (10^6 m^3)	Storage capacity (10^6 m^3	Depth of siltation (m)
	E	N				
Dam1	36 56 21.6	19 50 03.3	241	16	8.3	10.45
Dam2	36 58 06.1	19 50 25.8	181	5	Empty	6
Dam3	37 03 07.2	19 48 08.7	147	6	3	3.4

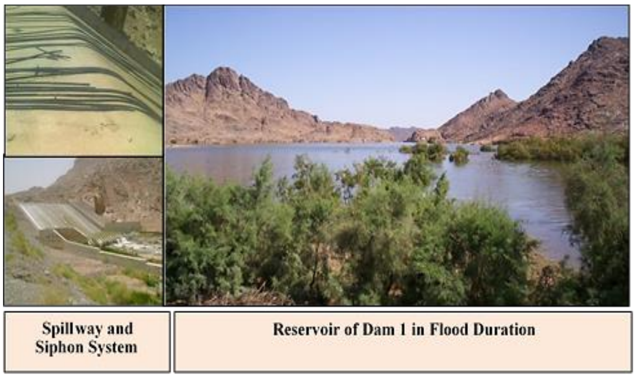


Fig. 16 Upper gate dam 1

difference of 200-400 m up to above 600 m, and a natural grade of 20°-30°. Inlet and outlet areas of Dams are given in Table 2. The dams’ site is located in the downstream Wadi channel of the Arbaat. Under the existing conditions, the reservoirs’ areas upstream of the dam have silted to be flat with weeds springing up and a small number of flows in the reservoir. Flows exist in the downstream Wadi channel throughout the year for water supply. The trend of the Khor is nearly E-W. The Wadi channel is U-shaped and 60 m wide. Table 3 and Fig. 15 describe the location and elevation of the three dams. The design storage capacity, storage capacity in 2013, and depth of siltation in 2013 are also revealed. It can be seen that the distance between Upper Gate Dam1 and SPC Dam2 is about 3.2 km. The distance between SPC Dam2 and Fourth Dam3 is about 11.4 km. The distance between Upper Gate Dam1 and Fourth Dam 3 is about 14.55 km. The elevation of Port Sudan City and the Red Sea near the City is about 6-10 m and 0 m, respectively. The Red Sea near the city about (0) m. Also, the distance between Upper Gate and Middle Gate is about 10.6 km and the distance between the Middle Gate and Lower Gate about 3.55 km.

2.2.1 Upper gate dam 1

Upper Gate Dam 1 constructed in early 2005 and was designed for the water supply of Port Sudan town up to the year 2045 in a sustainable manner (Fig. 16). Nevertheless, the Upper Gate Reservoir could not be up to the expectation because of siltation. Dam 1 is an earth dam with a designed capacity of 16*106 m^3. The features of the dam are given in Table 4.

Table 4 Upper dam’s characteristics

Dam’s characteristics	Value
Dam crest level (Height)	28 m
Spillway (Storage height)	24 m
Spillway length	60 m
Bottom length of dam	120 m
Top length of dam	300 m
Crest width	6 m
Sluice gates dimensions	3*2*3 m
Designed storage capacity	16 Mm^3
Storage capacity (2013)	8.3 Mm^3
Supply duration	12 month/year
Silt height	10.45 m
Silt statue	28 m

2.2.1.1 Dam components structures

The dam is located approximately 37 km northwest of Port Sudan, around 3 km upstream of the Upper Gate Masonry Dam (SPA Dam 2).

The major structures include clay core, rocks, and spillway and bottom sluice gates. The water-retaining structure (embankment of the dam) is a clay core rock-fill dam, 28 m high and 170 m long with the dam crest width of 6 m and the bottom width of 17.4 m, the ratio of the upstreamand downstream slopes is 1:3, and the clay core is 4 m wide. The spillway dam is 24 m high and 50 m wide. There are horizontal culverts with three gates (3.0×2.0 m) and hydraulically operating control system for spilling surplus or undesired water. Currently, the culvert gates are buried under silt of 10.5 m height. This is partly due to lack of protection system in the dam design, horizontal

Fig. 17 Sluice gate and spillway of upper gate dam 1

Fig. 18 Sluice gate of upper upstream gate dam 1

positioning of the culverts, and partly due to high silt and debris in the stream water with a steep gradient. The Design Capacity (Q) of the dam was calculated by using Eq. 1 and following the Hydraulic Design Details of U/S Upper Gate Dam 1, given by Shora (2002).

$$Q = C.L.H^{3/2} \quad (1)$$

where:

Q = Design Capacity in m^3/sec; C = Discharge Coefficient; L = Spillway Length in (m); H = Head of water above the crest (m), with maximum Flow Depth = 4.7 m.

The Hydraulic Design Details of U/S Upper Gate Dam 1 are as follow:

(i) Dam Embankment Details:
-Dam Height = 28 m
-Upstream Slope = 2.5:1
-Downstream Slope = 2:1
-Bottom length of dam = 120 m
-Top length of dam = 300 m
(ii) Spillway Design:
-Type of Spillway: Chute Spillway Type
-Length of Spillway = 60 m
-Horizontal Crest of Spillway= 11m
-Curved Length = 8 m
-Discharge Coefficient for crested Weir = 1.67
-Maximum Spillway Capacity at Head Level equal to 4.3 m = 885 m^3/sec

Moreover, the sluice gates are located at the inlet to the ducts immediately to the north of the spillway. The purposes of the gates besides helping the spillway discharging more flows in an emergency are in the control of the reservoir pool level as desired. In addition to this, the operation of the sluice gate, especially during summer floods can be used to clean sediment deposited or accumulated near or in the vicinity of the dam body. The sluice gates can also be used to fill and control the level of the new proposed reservoir at the upper gate. The number of Sluice Gates is three corresponds to the three ducts shown in Fig. 18. The gates are 3 m high and 2 m wide. The gates made out of steel and operate semi- electrical. The discharge through the gates relation is given by Eq. (2) and the following details:

$$h = (0.5 + f.L/R)^* Q^2/2gA^2 + Q^2/2gA^2 \quad (2)$$

where

Q = Design Capacity in m^3/sec; h = Head above the centerline of the duct (m); f = Friction Coefficient (0.04); L = Duct Length (m); A = Area of Sluice gates; R = Hydraulic Radius.

(i) Leading Channel (Duct):
Leading Channel Width = 12 m.
Leading Channel Length extended beyond the downstream of toe dam = 30 m.
Velocity in Channel reduce to = 4.7 m/sec.
(ii) Volumes of Dam Earth Section:
Core (Silty, Clay – Impervious) = 36792 m^3
Blanket (Silty, Clay – Impervious) = 14,400 m^3
Shells (Silt, Sand, Gravel –Pervious) = 19 5768 m^3
Length of Blanket = 10 h= 240 m from Toe of Core
(iii) Clay Core Materials: Silty Clay Materials.

2.2.2 Sea port corporation (SPC) dam 2

Called Sea Port Corporation Dam is a masonry dam, and the SPC Dam 2 site location is approximately 3.2 Km downstream from Dam 1, also the SPC Dam reservoir regulates the runoff into the reservoir from the Upper Gate Dam 1. The primary purpose of the reservoir is to supply water to Port Sudan 45 km downstream of the dam site with a population of 800,000. The dam was built in 2002 with a total reservoir capacity of approximately 5 million m^3, a maximum daily water supply capacity was about 25,000 m^3, and minimum daily water supply capacity of 5,000 m^3. In the past few years, it has become collecting the spilled water from the Upper Gate Dam 1, and channeling water through pipelines to the main transmission line of 20-inch diameter to Port Sudan after passing through slow sand filters of 4000 m^2 area. The Wadi channel nearby dam mainly consists of alluvial – proluvial gravels, stone with the amount of fine sand and silt, and clay, resulting in a thickness of approximately 5 m according to initial estimates. Both banks of the dam site area are bed Rock Mountains with a top elevation of 304-434 m and a natural grade of 15°-25° featured by broken rocks. The Wadi bottom elevation is approximately 190 m and longitudinal slope of the river 2%. Under the existing conditions, the Wadi valley is wide and shallow. The characteristics of the dam are given in Table 5.

Table 5 SPC Dam's characteristics

Dam's characteristics	Value
Dam crest level (Height)	13 m
Spillway (Storage height)	10 m
Spillway length	20 m
Bottom length of dam	70 m
Top length of dam	10 m
Crest width	2m
Sluice gates dimensions	d = 2*1.2 m
Designed storage capacity	5 Mm^3
Storage capacity (2014)	0 Mm^3
Supply duration	12 month/year
Silt height	6 m
Silt statue	Dry Silt

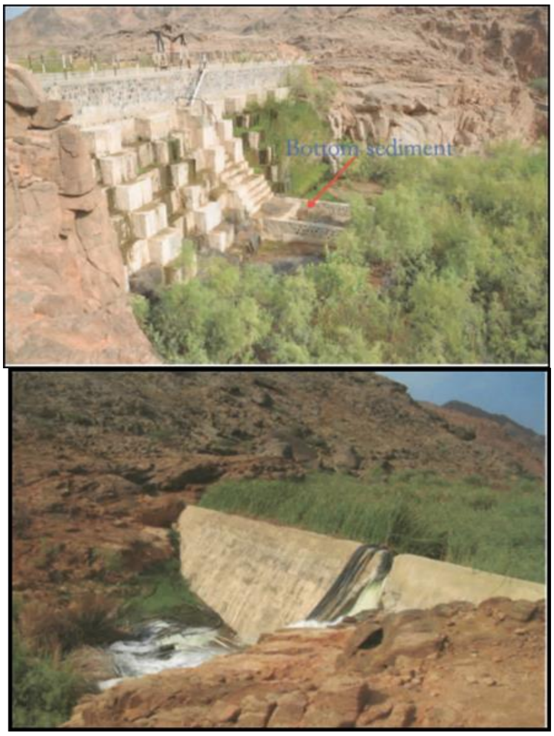


Fig. 19 Sluice gate and spillway of SPC Dam 2

Table 6 Fourth reservoir dam's features.

Dam's characteristics	Value
Dam crest level (Height)	13 m
Spillway (Storage height)	8 m
Spillway length	-
Bottom length of dam	-
Top length of dam	-
Crest width	4 m
Sluice gates dimensions	d = 3*1.2 m
Designed storage capacity	6 Mm^3
Storage capacity (2014)	3 Mm^3
Supply duration	12 month/year
Silt Height	3.4 m

2.2.2.1 Component structures of dam 2

The major structures include embankment dam, spillway and bottom sluice gate. The water-retaining structure (embankment) is a stone masonry gravity dam with the height of water retaining section of 13 m, the dam length of 70 m, the dam crest width of 2 m and the bottom width of 10 m. The spillway dam section is 10 m high and 45 m wide. The spillway is set on the rocks at left dam abutment Two bottom sluices (diameter: 1.2 m) are set at the middle section of the control structures of dam section. There are two 20 – inch steel water pipes (Fig. 19).

2.2.3 Lower gate earth dam (fourth reservoir, dam 3)

In 1991, an emergency program was launched to provide the city of Port Sudan with water; signs were indicating that the city was going to face a critical time due to water shortage at Wadi Arbaat resources. In this crash program, four dams were constructed within the Wadi. Three of these dams are recharge dams constructed immediately downstream of the upper gate, but on the sides of the Wadi.

The Fourth dam has a capacity of 6 million cubic meters. This dam is located out of the main Wadi course where small hill on the south side of the Wadi forms a large passage with the mountains. The downstream end of this pass is closed, forming the dam and the flow is diverted toward the upstream inlet from the Wadi via a diversion embankment (Consult 2002). The dam was designed to serve two purposes: store water and recharge the aquifer zone. The characteristics of the dam are given in Table 6.

2.2.3.1 Component structures of dam 3

The dam was designed to provide water through dam embankment, which is an earth dam, as shown in Fig. 20. Also, as illustrated in Fig. 21, the spillway which is entirely separate from the dam was provided. In this dam, pipes were installed underneath the dam to bring water from an inlet well presently blocked by silt and water is siphoned by gravity through 15 pipes, 2-3 inches' diameter polyethylene type to the transmissions line to Port Sudan. Moreover, four terraces were constructed upstream of the lower gate dam for checking the water velocity for recharging the aquifer zone, but has been washed and depositing a silt layer that resulted in lowering the infiltration rate drastically. The surface water supply from Arbaat is currently about 16,000 m^3/day.

2.2.4 Rainfall data analysis

2.2.4.1 Maximum rainfall events

In general, studying the extreme hydrological events required choosing the largest or smallest events. However, for rainfall-runoff hydrological modelling and sediment transport prediction, the researcher is more interested in the largest extreme events that have a large probability of creating maximum runoff. The Rainfall-runoff analysis using HEC-HMS model indicated that the surface-runoff in the Arbaat watershed occurs when rainfall exceeds 35 mm in one day or 50 mm in two consecutive days. Moreover, the maximum daily rainfall events were analyzed using frequency analysis. The main purpose of the frequency analysis of hydrological data is to relate the magnitude of

Fig. 20 Fourth reservoir embankment and intake

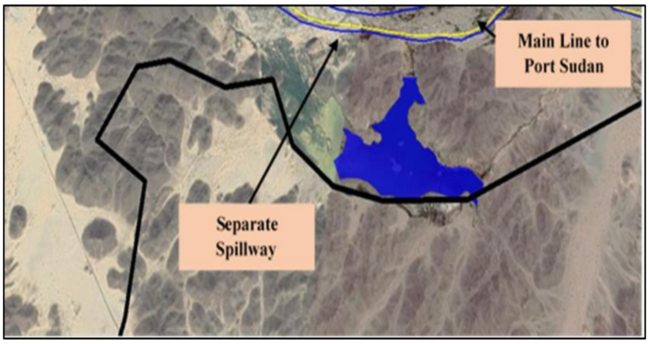


Fig. 21 Spillway separately of FR Dam 3

extreme values to their frequency of occurrence through the use of probability distribution.

2.2.4.2 Depth-duration-frequency-intensity of Arbaat rainfall

In several hydraulic structures, such as those related to floods, the possibility of a particular, severe rainfall of specific duration will be significant. In general, the rainfall duration can be categorized as (i) short duration, which is lasting from 1 minute to 1 hour, (ii) intermediate duration, from 1 to 24 hours, and (iii) long duration which is more than 24 hours. In arid and semi-arid zones like Arbaat area, which generally have short-duration rainfall, a maximum duration of 2 hours is suggested. The Depth- Duration-Frequency (DDF) relationships have a considerable effect on this investigation for estimation of the peak discharge (Qpeak) with HEC-HMS. Unfortunately, in the study area, the data for 24-hour of rainfall are available. Hence, a study of sediment prediction is constrained to either consider a uniform precipitation distribution over the total storm duration, which results in the underestimation of peak discharges or assuming the rainfall depth record for each storm by duration 120 minute (2 hours). For consistency, the Gumbel distribution was used for all frequency analysis in this study.

2.2.4.3 Gumbel's distribution:

Gumbel distribution is one of the most widely used probability distribution functions for extreme values in hydrologic and meteorologic studies for prediction of maximum rainfall, flood peak (Soliman 2010). The calculation of maximum rainfall is essential for the computing Suspended Sediment Discharge (SSD) and then sediment bed load. For this purpose, the Gumbel method has been used for this research work. The relation between the annual maximum rainfall, X_T, and the corresponding return period T, for Arbaat watershed area, is given by Gumbel equation as PMP

$$X_T = 38.4 + 32.9\left(-\ln\left(\mathrm{Ln}\frac{T}{T-1}\right)\right) \to 5 \tag{3}$$

The return period (T) of a design rainfall storm should be based on economic efficiency (Federation and Engineers 1992). However, in practice, the return period (T) is usually selected based on the level of hydraulic structures. It was found that the return period of 100 years from Table 3 provided rainfall value of 141.6 millimeters, which is almost the same as the PMP. As a result, 141.6 mm will be the value taken for HEC-HMS model.

2.2.4.4 Application of gumbel distribution and Weibull formula:

The Weibull formula, as shown in Eq. (2), was used for frequency analysis of rainfall where the probability of occurrence of an event whose magnitude is equal to or in excess of a specified magnitude X is denoted by P, as follow

$$r = \frac{m}{N+1}, r = \frac{N+1}{m} \tag{4}$$

P = the probability rainfall equaled or exceeded,
T = the Return period (recurrence interval is given as:
T = 1/P,m is the order number (m = 1, 2, 3, 4, N),
m = N = number of years on record
N is the sample size (number of records)

3. Results and discussion

3.1 Research area

The three dams (UG, SPC, and FR) are located in Red Sea State Wadi Arbaat, Port Sudan Province, Sudan. These dams located in steep slope area mainly are known Red Sea Mountain. Most Wadies located on Red Sea State such as Wadi Arbaat originate from the Red Sea Hills (300-1500 m on average, above sea level) and empties their waters in the Red Sea Coast (0.0 m above sea level), Khor Arbaat suffers from a severe decline with the steep slope of 6-10 m/km. Therefore, the Khor carries large quantities of sediments, which deposit in dams' reservoirs during the flood periods. Khor Arbaat takes high flood in summer (June, July, and August) and winter (November, December) seasons, but these quantities of water are useless. The location of the three dams is shown in Fig. 10.

3.2 Assessment of sedimentation problems on three dams

This study focuses on sediment effects on these Dams components by studying the changes that occurred on these dams in terms of storage capacity and their impact on the water supply.

3.2.1 Upper gate dam 1

The importance of this dam for it is the largest dam in the Red Sea State. Upper Gate Dam 1 constructed in early 2004 was designed for the water supply of Port Sudan town up to the year 2045 in a sustainable manner. Nevertheless, the Upper Gate Reservoir could not be up to the expectation because of siltation. The steep slopes of the watershed, the rainfall, the soil type of the catchments area, and the less vegetation cover make the situation more conducive for greater erosion to take place in the Upper Gate Dam 1catchment throughout rainy seasons.

3.2.1.1 Bathymetry survey of dam 1

Bathymetry surveys were conducted in March 2013 by the Ministry of Water Resources and Electricity (Sudan Dams Implementation Unit, Hydrology Department DIU). The purpose of bathymetry surveys is to identify the real size of the reservoir after silting occurred in the lake during the operation period of the dam. The results showed that the size of the reservoir at the level of 223.98 m was 2.6 million m^3. The results also showed that the total size of the reservoir at a maximum level of 231.08 m is 8.3 million m^3 with a total area of 0.797 km^2. These summarized data are shown in Fig. 23 and Table 7. Topographic surveys during the design in 2002 included a contour map that has been constructed by Shora Consult for reservoir location; the contour line started from level 207 m to 240 m. Fig. 24 (A) and Table 7 show data for 2013 and level area, and volume of Arbaat U/S upper gate reservoir (Dam Site Level 207). The Digital Elevation Model (DEM) of a whole area of Arbaat Watershed is shown in Fig. 25.

A bathymetry survey performed in 2013 for the Upper Gate Dam 1 Reservoir; and (storage – elevation) curves show a reduction in storage capacity due to siltation of the reservoir.

3.2.1.2 Measurement of sedimentation depth inside upper gate dam 1

The field investigation carried out on 9-12-2014 and 23-1-2019 including the siltation measurements inside Upper Gate Dam1 and. The depth of sedimentation existed in Upper Gate Dam1 was measured 10.45 m and 16.58 m, respectively. The details of this measurement data are shown in Tables 8 and 9 and Figs 18 and 19. Through Tables 8 and 9 above, we announce the increase in sediments' depth of about 6 meters in five years only; this is an unsafe indication of the dam.

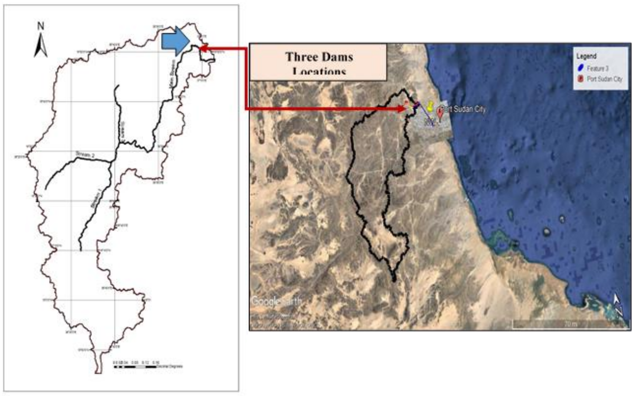


Fig. 22 Location map of the three dams

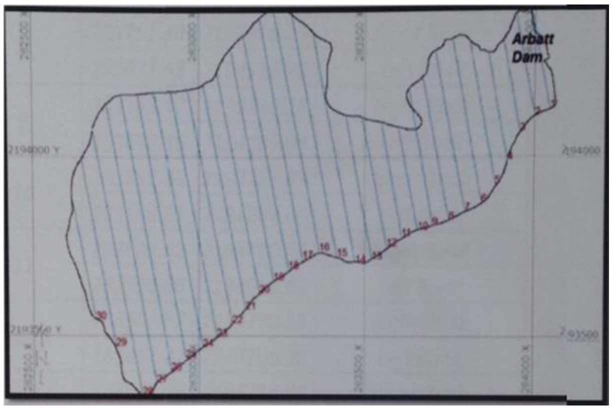
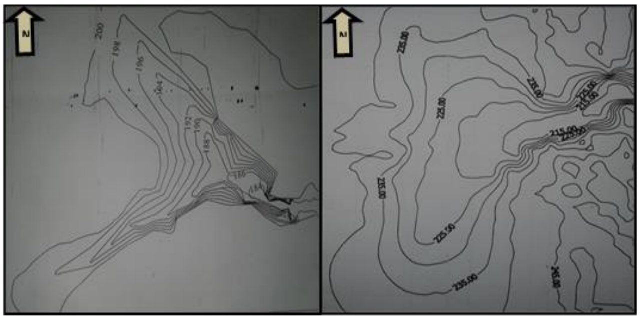


Fig. 23 Bathymetry survey for dam 1 reservoir 2013



A. SPC Reservoir – 2001, Scale: 1:15000 B. U/S Upper Gate Reservoir2002, Scale: 1:80000

Fig. 24 Contour maps of SPC and U/S upper gate reservoir (constructed by SHORA CONSULT)

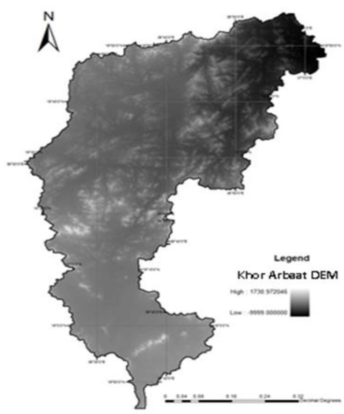


Fig. 25 Digital elevation model (DEM) of Arbaat watershed

Table 7 Topographic surveys (2002) and bathymetric surveyed data (2013)

Contour	Shora 2002		DIU 2013		Storage(m^3) 2015	Prediction in 2020	
	Area (m^2)	Volume (m^3)	Area (m^2)	Volume in 2013		Area (m^2)	Volume (m^3)
210	59912	89,868	Silted	Silted	Silted	Silted	Silted
212	146032	295,812	Silted	Silted	Silted	Silted	Silted
214	192339	634,183	Silted	Silted	Silted	Silted	Silted
216	257942	1,084464	Silted	Silted	Silted	Silted	Silted
218	379,579	1,721,985	Silted	Silted	Silted	Silted	Silted
220	549,145	2,650,709	6830.37	32,970	Silted	Silted	Silted
221	638,450	3,244,507	8923.72	45,349	Silted	Silted	Silted
222	746,168	3,936,816	206513	1,089570	Silted	Silted	Silted
224	989,855	5,672,839	462668	2,651,540	1896215.25	Silted	Silted
225	1,161,852	674,8693	593744	3,448,800	2693475.25	456488	971804.9
226	1,287,599	797,3490	568771	4,245,080	3312977.5	462082.6	1196181
227	1,421,814	9,328,126	675722	5,043,320	3972118.5	568771	1472363
228	1,566,184	10,822,25	730050	5,840,400	4594937.5	630415	1689162
229	1,795,100	12,502,767	737539	6,637,850	5171620.75	648933.3	1937883
230	2,029,325	14,414,979	743511	7,435,110	5690142.75	663785	2223227
231	2,215,756	16,537519	797000	8,232,370	6156082.75	719814.9	2550587

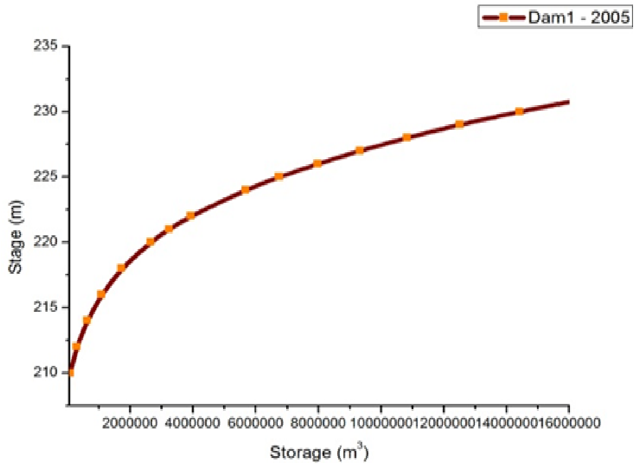


Fig. 26 Storage for U/G Dam 1 Reservoir in 2005 (Storage = 16,000,000 m^3)

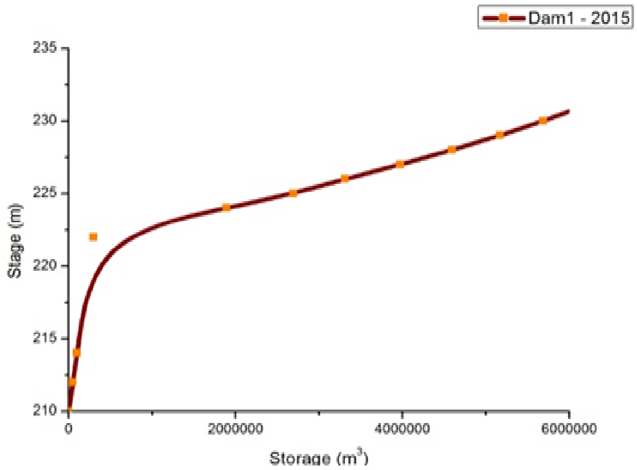


Fig. 28 Storage for U/G Dam 1 Reservoir in 2015 (Storage < 6,200,000 m^3)

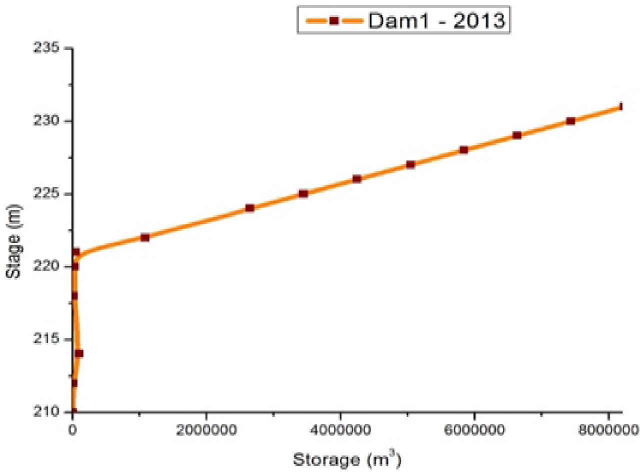


Fig. 27 Storage for U/G Dam **1** Reservoir in 2013 (Storage < 8,300,000 m^3)

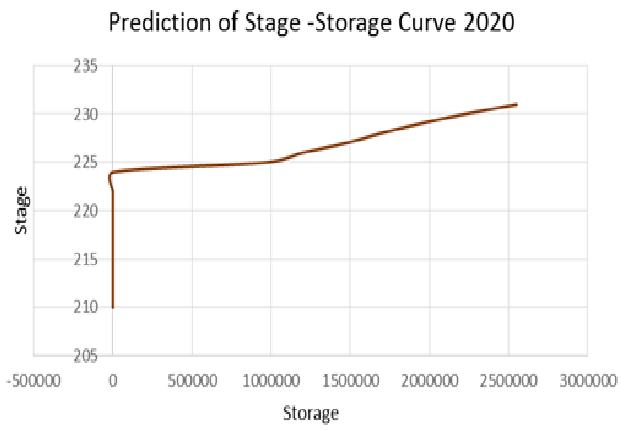


Fig. 29 Storage for U/G Dam 1 Reservoir, in 2020 (Storage < 3,000,000 m^3)

Table 8 Measurement of sedimentation depth inside upper gate dam 1, 2014

Description of measurements	Points	Location	Elevation (m)	Measure from tower	Depth from ground (m)
Date: 9-12-2014 Time: 1.00 pm Location: Control room of gates. Coordinates: N19 50 02.6 E36 56 21.3 Equipment: 1- GPS instrument (Garmin 2) for positing and directions. 2- 30 m tape measure.	1	Bridge	235.30	0.0	28.3
	2	Embankment	235.00	0.3	28
	3	Spillway	231.00	4.3	24
	4	Water	225.8	9.5	18.8
	5	Siltation	217.45	17.85	10.45
	6	Ground in side dam	207.00	28.3	0
	- Reference point: Reference point inside tower. - Height of dam 28 m. - Height of spillway 24 m. - Depth of siltation = 28.3 – 17.85= 10.45 m - Depth of water = 17.85– 9.5= 8.35 m				

Table 9 Measurement of sedimentation depth inside upper gate dam 1, 2019

Description of measurements	Points	Location	Elevation (m)	Measure from tower	Depth from ground (m)
Date: 23-1-2019 Time: 10.15 A.M. Location: Control Room of Gates Coordinates: N19 50 05.6 E36 56 35.7 Equipment: 1- GPS instrument (Garmin 2) for positing and directions. 2- 50 m tape measure. 3- Camera Canon	1	Bridge	236.28	0.0	29.28
	2	Embankment	235.08	1.20	28
	3	Spillway	231.08	5.50	24
	4	Water	229.08	5.35	22.02
	5	Siltation	223.58	12.70	16.58
	6	Ground in side dam	207.00	29.28	0
	- Reference point: Reference point inside tower (50 meters from the crest of dam). - Height of dam 28 m. - Height of spillway 24 m. - Depth of Siltation = 223.58-207.00 = 16.58 m - Depth of Water = 229.08 – 223.58 = 5.5 m, Distance between Tower an Embankment = 52.28 m				

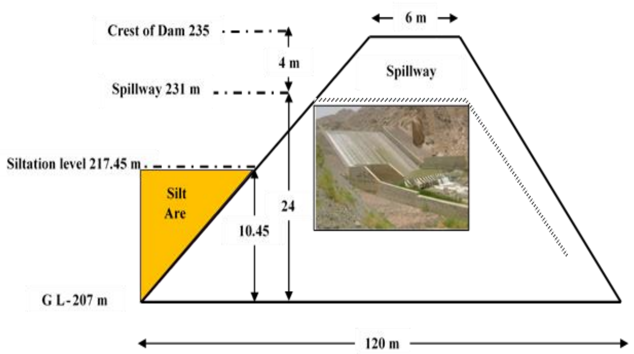


Fig. 30 Measurement of sedimentation depth section inside dam1, 2014

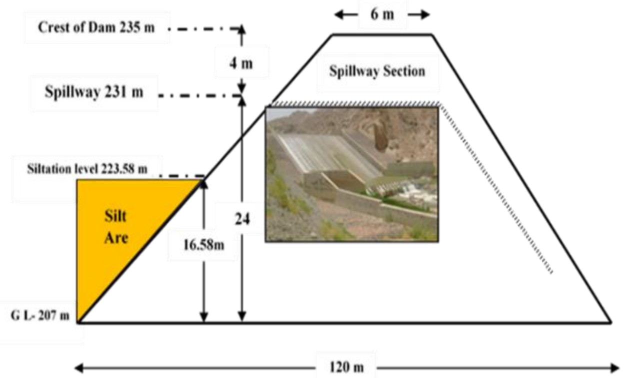


Fig. 31 Measurement of sedimentation depth section inside dam1, 2019

3.2.1.3 Problems and changes of dam 1

As a Major problem faced Upper Gate Dam after the rainy season with the first flooding in 2006 after the dam construction; it was found that the Hydraulic Sluice Gates did not work at times as a result of the rise of silt. Thus, the withdrawal of water from the dam to Port Sudan city was achieved by using a siphon system as shown in Fig. 32. In addition, serious silting features was seen in the reservoir area. It was found that the current reservoir silting thickness were 16.5 m and the average annual silting thickness 1.3 - 1.5 m based on the annual flood discharges. The beneficial reservoir capacity has been severely damaged. If no measures were to be taken, the silting elevation would be build-up to the spillway dam crest with the rising of silting surface elevation, and the beneficial reservoir capacity would be reduced to zero gradually in 2023. The flood control capacity will also be reduced, resulting in dissatisfaction to the flood control requirement and flooding over the dam. This dam will undoubtedly be filled with sediments in 2023. Besides, the culverts gates are buried under silt of 16.5 m height. This is partly due to lack of protection system in the

Fig. 32 UG Dam 1 (Siphon system on spillway due to gates were closed as a result of the rise of the silt)

dam design, horizontal positioning of the culverts, and partly due to high silt and debris in the Khor water with a steep gradient.

3.2.2 Sea port corporation dam 2

In the year of 2012, the dam was removed by the armed performed on 29-12-2014. Measurements indicated that the depth of sedimentation existed in SPA Dam 2 about 6 m, as illustrated in Fig. 33.

3.2.2.1 Problems and changes of dam 2

There are few major problems in the reservoir of dam 2. Both bottom sluices and drainpipes were blocked due to silting. It is understood that the bottom sluice gate has never forces of the corps as a result of inflation silting and thickness of silting to 6 meters, as shown in Fig. 21. On the other hand, the small capacity of the dam is one of the reasons for the fast silting of the reservoirs.

3.2.2.2 Dry sediments in sea port corporation dam 2

The SPC Dam 2 in the year 2012 was removed because of inflation silting and thickness of silting to 6 meters. The measurements of dry siltation inside SPC Dam was been opened due to the lack of lifting force of the hoist caused by excessive silting. For that reason, the withdrawal of water from the dam to Port Sudan city was attained by using a siphon system, as shown in above Fig. 33. At 2010, the silting elevation in the reservoir area has reached the spillway dam crest. Also, The Sea Port Corporation (Dam 2) in the year 2012 was removed by the Sudanese armed forces of the corps, as a result of inflation silting and thickness of silting to 6 m as shown in Fig. 33. Moreover, there are four major causes for filled, which are the bottom sluice gates fail to flush sediments; the discharge capacity of silting flush is too low. Silting in the flood plain is formed due to long-period retention of flood in the reservoir area caused by low discharge capacity in case of the flood, and silting is caused indirectly by reduction of sediment

3.2.3 Fourth reservoir dam 3

Water stored in this reservoir is turbid before constricting Dam 1 and Dam 2, and recently slow sand filters have been erected to improve water quality physically and bacteriological. However, there is an acute water quality problem occurred this year 2001/2002 in the fourth reservoir. Due to the massive extraction from this reservoir water level dropped from 12 m to 2 m, salinity at

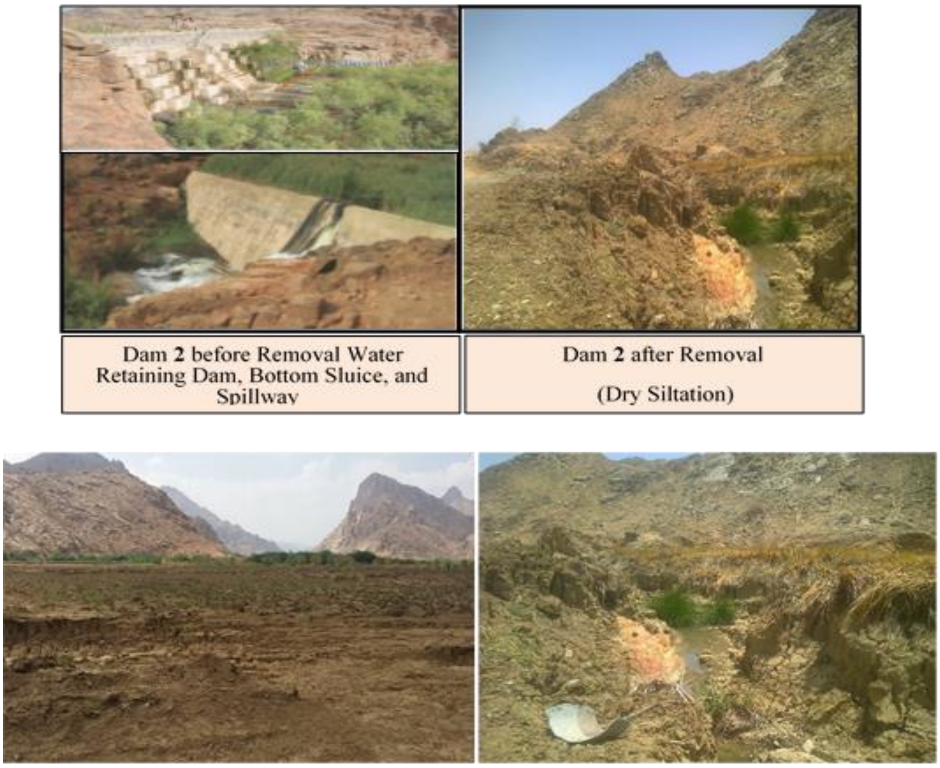


Fig. 33 SPC dam 2 before removal and dry siltation on SPC reservoir, 2019

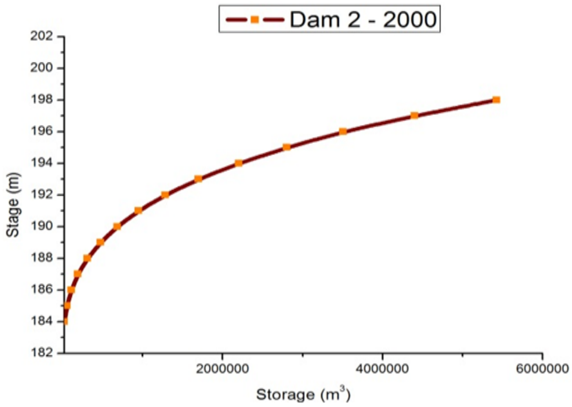


Fig. 34 Storage for SPC Dam 2 Reservoir, in 2000 (Storage = 5,000,000 $m^{3)}$

this level increased substantially due to the interaction between the soared surface water and shallow groundwater aquifer. Small fish and other living aquatic organism being unable to tolerate the sudden increase in the salinity level died, creating an unfavorable water quality condition (organic pollution). Extraction of water from the reservoir was held up immediately due to this incidence.

Likewise, there are some major problems occurred in dam 3. Due to the problem of siltation, the capacity has practically fall down to 3.5 million cubic meters. Therefore, the reservoir needs some rehabilitation. The outlet of the reservoir to the downstream has silted up. For a quick solution, the siphoning system has been proposed with small diameter pipes. Also, the steel water pipe was blocked due to its lower location and lack of layered water intake.

3.3 The existing situation of the three dams

Sedimentation of a reservoir created by a dam constructed on a natural watercourse is inevitable. The problem of concern is that the rate of sedimentation and the period of time, which will elapse before the usefulness of the storage work is severely impaired or destroyed. The silting of dam reservoirs is the most challenging problem in Sudan. Sedimentation adversely affects reservoir capacity. The consequences are very complex because dams usually serve multiple purposes. Sedimentation also affects the reservoir by reducing water depth and favoring the development of aquatic growth, blocking bottom outlets, gates and valves. Many dams constructed to store water for irrigation and/or drinking purposes are being silted up while they were under construction or just after construction. Upper Gate dam and others (SPA, Fourth Reservoir) constructed between years 1991 and 2005 were primarily planned to solve the drinking water problem of Port Sudan town sustainably. The dams were found to be feasible in terms of cost consideration and judicious use of abundantly available local material. Nevertheless, the Upper Gate, Fourth, Sea Port Corporation Reservoirs could not be up to the expectation because of siltation.

Their storage capacities are $16*10^6$, $5*10^6$, and $6*10^6$ m^3 respectively, therefore, small capacities of these dams lead to inflation silt in a limited period of time. Bathymetric surveys in 2013 have been undertaken to estimate the extent of the sediment in the reservoir and showed that sediments are accumulating at a rate of 0.84 Mm^3/year for the intervening period (Abdalla 2013). Siltation of the reservoir has a considerable impact on the reservoir functions. Today the storage is approximately 3,000,000 m^3. The rating curves are shown in above Figs. 14-17 and 22.

3.4 Measures for reservoir sedimentation

There are two methods available to reduce the reservoir sedimentation, which is sediment retention in the catchment area, and sediment removal from the reservoir. Besides, to achieve the sustainable use of reservoirs, the following basic sediment control strategies could be applied. (i) Reduce Sediment Inflow, in which sediment delivery to the reservoir can be reduced by techniques, such as erosion control and upstream sediment trapping, (ii) Route Sediments, in which some or the entire inflowing sediment load may be hydraulically routed beyond the storage pool by techniques, such as drawdown during sediment-laden floods, off-stream reservoirs, sediment bypass and venting of turbid density currents, (iii) Sediment Removal, where hydraulic flushing, hydraulic dredging, or dry excavation may periodically remove deposited sediments, (iv) Provide large storage volume, in which reservoir benefits may be considered sustainable if a storage volume exceeds the volume of the sediment supply in the tributary watershed. The required sediment storage volume may be included within the reservoir pool or in one or more upstream impoundments.

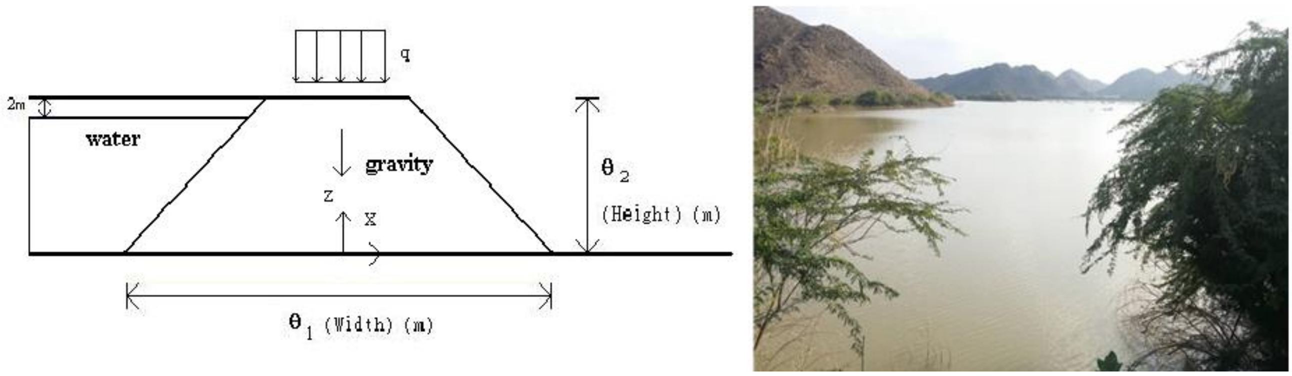


Fig. 35 Embankment of fourth reservoir dam 3

4. Conclusions

There are general problems due to soil erosion and deposition in worldwide, and the need for improved understanding of the properties of sediment transport is presently considered as one of the most important topics that have been highlighted in sedimentation with dams, especially more than half of the reservoirs of the world face problems of siltation. Challenges are presented in studying the sedimentation of Khor Arbaat, mainly resulted from inaccessibility, rugged, and inhospitable terrain, and historical lack of foresight concerning the need to have these areas adequately gauged. Predictive tools for sediment transport, such as the erosion of the soil of watershed, silting of dam reservoirs and water quality are generally data-driven. Lack of adequate sediment concentration records, measurements stations and previous studies poses severe problems for studying the sediment behaviors in this areas. From the above points, it can be concluded that there is a need to develop appropriate techniques for studying the components of sediment transport and the equations that describe them to design sediment-settling basin and support integrated siltation management in order to preserve the useful life of reservoirs in Khor Arbaat. Finally, there is an optimum design of dams located on steeper slope areas, and feasible solution to the problems mentioned above. Moreover, the problem of reservoir sedimentation can be brought under control by the construction of upstream sediment traps and by developing operational actions for sediment transmitting and sediment removal from current reservoirs.

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