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Hydraulic Design of Sediment-Trapping Basin in Wadis Using Empirical Equations and Deposition Processes

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Abstract: Reservoirs overflow during flood season because of sedimentation cycles, which severely affects their effectiveness. Siltation is a major problem in dams constructed in waterways in arid and semi-arid areas. Therefore, the reservoirs in wadis lose their capacity due to sedimentation. This study determines an optimal design of the trapping basin on steep slope areas for Wadi Bishah in the Asir region of southwestern Saudi Arabia. The empirical design criteria of the sediment-trapping basin is used to mitigate the effects of sedimentation in the King Fahd Dam. The empirical design of the trapping basin constructed upstream of the dam located in the wadi is presented. Moreover, the annual suspended and bed sediment load (Q_s and Q_b) techniques for estimating the volume of sediments are used, and the relationship between the sediment trapping efficiency and size is determined. The sediment trapping in Wadi Bishah upstream sediment-trapping basins is selected to reduce the amount of sediment. One of the important results of this study tries to create a new concept to trap sediment in wadis, which are located in arid and semi-arid areas. The results obtained were evaluated using theoretical and empirical equations to determine the appropriate size of the basin. The results demonstrate that the optimal dimensions for the sediment confinement basin are $L_b \times W_b \times h_s = 3500 \times 500 \times 1.5$ m. Also, for these dimensions, the basin efficiency was assumed to be in the range of 60–70%. The trap basin should be constructed at open check dams upstream (U/S) of the proposed basin to enhance its efficiency. Further investigation is required to understand the transport and deposition of sediments, particularly fine sediments in the basin. Additionally, the effects of sediment traps in Wadi Bishah should be assessed during the construction of these structures to aid water resource management and mitigate flood disasters.

Keywords: Wadi Bishah; King Fahad Dam; annual total load; empirical equations; sediment-trapping basin

Citation: Taha, A.T.B.; Aldrees, A.; Moussa, A.M.A. Hydraulic Design of Sediment-Trapping Basin in Wadis Using Empirical Equations and Deposition Processes. *Processes* **2023**, *11*, 2729. https://doi.org/10.3390/pr11092729

Academic Editors: Pastora Isabel Vega Cruz and Qingbang Meng

Received: 20 May 2023
Revised: 18 August 2023
Accepted: 28 August 2023
Published: 12 September 2023

1. Introduction

The sedimentation of reservoirs is a severe problem encountered in dams globally. Therefore, it is crucial to develop methods to prevent the sedimentation of dams. Siltation is a significant problem in barriers. Particularly, dams built in arid and semi-arid waterways are affected by siltation. Consequently, reservoirs lose their capacity due to the sedimentation process and problems such as the clogging of outlet structures. Two methods can be used to reduce reservoir sedimentation, namely sediment retention in the watershed area and sediment removal from the reservoir [1]. Preventing erosion is generally preferable to capturing sediment from eroded areas. Other methods such as vegetation are considered infeasible. Hence, sediment-trapping basins are typically selected as support systems. The World Commission on Dams (WCD) reported in 2000 that reservoirs worldwide are losing approximately 1% of their storage capacity annually [2]. Sedimentation causes severe problems in dams by reducing useful storage and the capacity of dams for flood routing.

This increases flooding hazards in the dam and downstream regions. Sediments can lead to additional problems and floating debris during floods in outlet structures by clogging them, resulting in dangerous situations or damaging trash screens [2,3]. If the sediment inflow is large relative to that of the reservoir storage capacity, the useful life of the reservoir is significantly reduced. For example, a small reservoir on the Solomon River near Osborne, Kansas, was filled with sediment during the first year of operation [4,5]. According to the (ICOLD 1989) definition, sediment deposition occurs when the flow enters the reservoir due to decreased flow velocity. Therefore, a reduction in the transport capacity of the flow occurs [6]. Several methods are used to estimate the annual sediment load trapped in dams because computing the sediment load in streams is difficult. The sediment load principle for rivers can be divided into three types—calculating the suspended load, estimating the bed load, and computing the total sediment load. Additionally, sedimentation models such as sedimentation and river hydraulics (SRH-1D) and CCHE2D models have been developed that can estimate the average sediment accumulation. These models have been applied to high dams in Egypt and the Angereb dam in Ethiopia. The SRH-1D model is one dimensional and contains 14 sediment transport equations. The basic data requirements for the model can be divided into three broad categories, namely geometric, spatial and temporal, hydraulic, and sediment data [7,8]. The modeling approach using CCHE2D has proven to be a useful tool to monitor future water flow and sediment deposition in reservoirs [9].

Morris and Fan (1997) describe two strategies to reduce the sediment yield entering a reservoir: either prevent erosion or trap eroded sediment before it reaches the reservoirs [10]. Figure 1 below is helpful in showing that there are several levels at which management effort can be targeted to reduce silt retention by reservoirs either using broad-scale land management type plans or aiming at the reservoir itself or the dam.

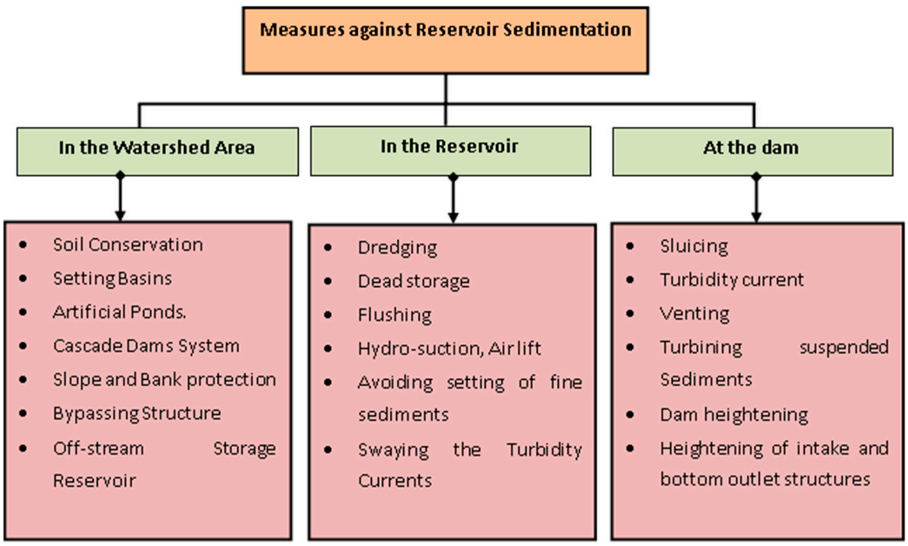

Figure 1. Sediment management and control diagram.

Sediment trapping by upstream dams is a crucial factor that controls sedimentation in reservoirs. However, there are two potential drawbacks of using this strategy as a long-term protection measure. First, the sediment retention capacity of the upstream reservoir is limited. Second, owners of upstream sites might modify their operations to allow sediment to flow downstream [10]. Torrential hazard mitigation is an important issue in steep slope areas, wherein morphological changes are characteristically short and abrupt, and new protection methods are constantly being developed [11]. Vegetation cover is crucial for preventing erosion and scouring in the watershed area. Therefore, clearing native vegetation is a well-documented cause of increased soil erosion [12]. Detention or trapping basins are constructed to trap sediments that might settle in the stream networks.

Settling basins are formed in reaches where the flow velocities are reduced to the limit required to ensure that sediment settles in the basin. The main advantage of settling basins is obtaining high sediment trap efficiency. In contrast, it has disadvantages such as the higher cost and reduction in the trap efficiency that occurs as basins fill with sediment. In order to achieve the required design standards, a settling basin is typically created adjacent to the headwork of hydroelectric plants to facilitate the settlement and exclusion of sediments [13,14]. Measures for sediment trap have been widely employed in the Yellow River basin. They comprise the construction of structures to retain sediment on slopes and within sediment settling basins and dam systems in channels called check dams, which capture sediment discharged from the slope. Additionally, these dams act as sources of water for residents and agricultural enterprises in several cases [15]. M.M et al. 2012 evaluated the settling basin design criteria directly downstream of the gravity canal intake for the prevention of sedimentation. Heavy sediment-laden rivers such as the Tana River feed Kenya's canal network. Sediment traps can significantly disrupt the sediment regime, severely affecting the river ecology and environmental conditions. However, these effects vary depending on the system. Hence, further research is required to determine the effect of sediment traps in mountain streams to assist resource managers to mitigate flooding hazards and ensure the future construction of these structures [16]. A popular metric to evaluate the efficacy of desanding facilities is trapping efficiency [17]. Current design guidelines include the transition zone and intake channel shapes to increase the efficiency of desanding facilities' trapping processes. The King Fahd Dam is annually exposed to a considerable volume of sediments, which decrease its design capacity. It is located in the Bishah Valley and was constructed in 1997. The King Fahad Dam is one of the largest dams in the Kingdom of Saudi Arabia, and it does not have a system for sediment control. Therefore, this study attempts to provide practical solutions for sedimentation in the King Fahd Dam using the sediment-trapping basin technique and empirical equations, considering the future performance and efficiency of these basins.

2. Materials and Methods

2.1. Study Area

Wadi Bishah is located in the southwestern region of Saudi Arabia, Wadi. It is a major drainage system which originates in the high-altitude mountain regions 2380–2112 m above the sea level. Figure 2 shows the location map of Wadi Bishah and King Fahad Dam (previously known as the Bishah dam) is located in the Asir province, which is approximately 35 km south and southwest (S_SW) of Bishah town, which is approximately 350 km SE of Taif city. The purpose of the dam is to recharge the aquifer and perform flood protection of the Bishah valley.

The main length of Wadi Bishah is 287 km from upstream (E: 42.20 N: 19.27) to downstream (E: 43.57 N: 21.32) represented as an inlet point and outlet point. The catchment area of the King Fahd Dam site is 7600 km^2. Figure 3 shows the topographic map of the study area constructed by Alshaikh in 2015 [18].

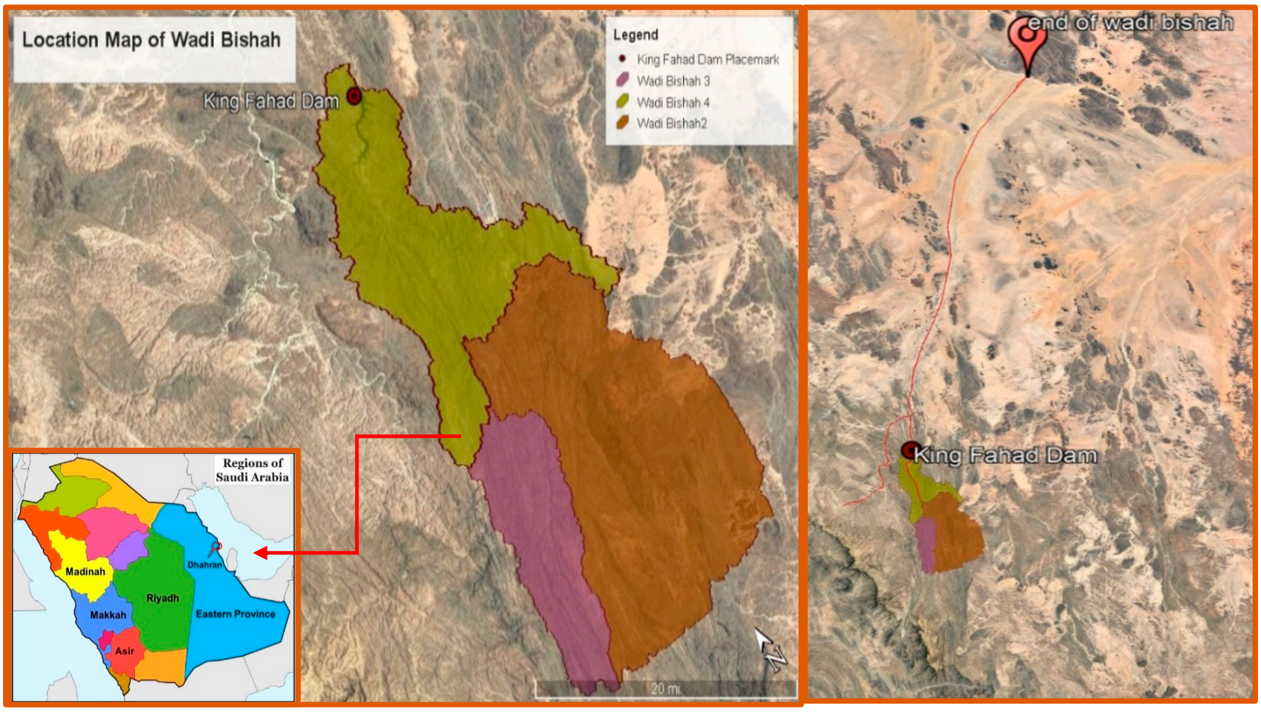

Figure 2. Location map of study area (Wadi Bishah).

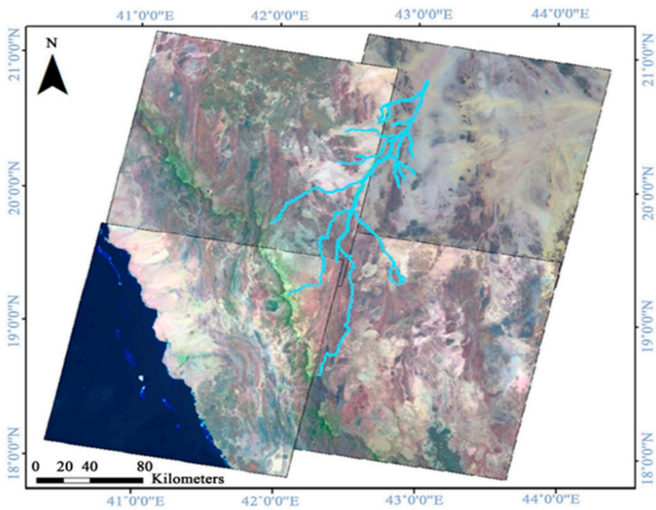

Figure 3. Satellite images covering the study area (Alshaikh, A. (2015)) ["Reprinted/adapted with permission from Ref. [19]. Copyright year 2015, Alshaikh, A and Scientific Research Publishing Inc"].

2.2. King Fahd Dam

The King Fahd Dam is the second largest gravity concrete dam (after the High Dam in Egypt in terms of size) in the Middle East and was constructed in 1997. The King Fahad Dam site is 3 km upstream of Aqiliyah village, as shown in Figure 4.

The King Fahad Dam is administered by the Ministry of Environment, Water, and Agriculture. It was the highest dam in Saudi Arabia (H = 68 m) before the construction of Hali Dam (H = 106 m) was completed in 2009. The reservoir of the King Fahad Dam has the largest storage capacity of 325,000,000 m^3. The water body upstream of the dam is used for controlled agriculture, irrigation of neighboring farms, replenishing groundwater, and compensating for surface water loss due to the drought along Wadi Bishah. The dam was constructed to protect the area from flooding, feed the water-bearing sedimentary layers, compensate for water withdrawal from the area's groundwater reservoir, and feed a water-purification plant.

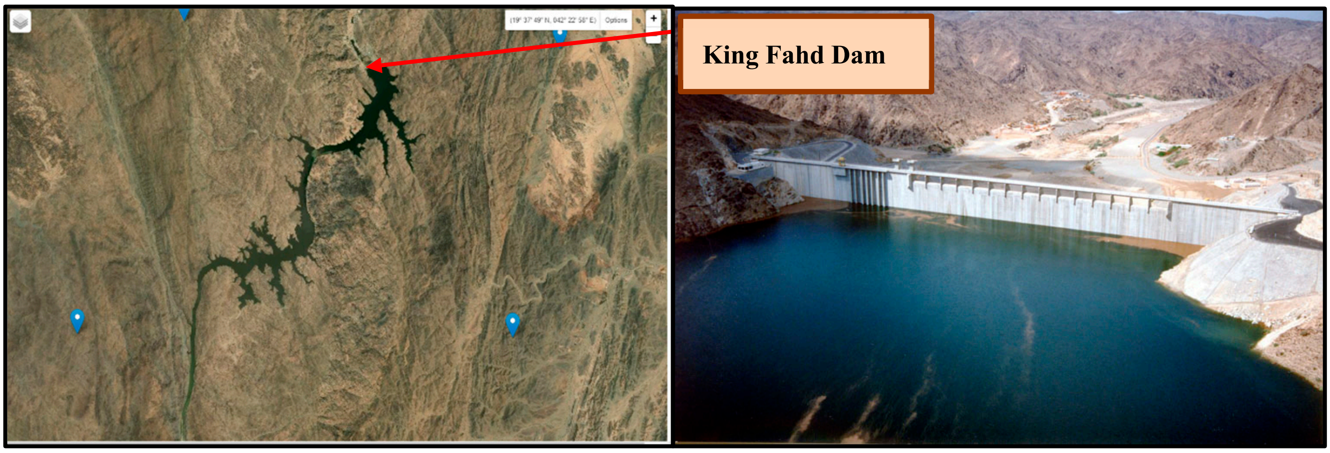

Figure 4. Location of the King Fahd Dam.

Table 1 lists the structural specifications of the King Fahd Dam (body of dam and dam control structures, (MOEAW, 1983).

Table 1. Specifications of King Fahd Dam and its reservoir.

Reservoir Data of King Fahd Dam	
Maximum Reservoir Level	1315.70 m above sea level (a.s.l)
Reservoir Level for Dead Storage	1283.00 m above sea level (a.s.l)
Maximum Reservoir Volume	325×10^6 m^3
Reservoir Volume for Flood Control	252×10^6 m^3
Dead Storage Volume	73×10^6 m^3
Details of King Fahd Dam	
Type	Concrete Gravity Dam
Crest Elevation	1318.00 m above sea level (a.s.l)
Crest Width	6 m
Crest Length	507.00 m
River Bed Elevation	1250.00 m above sea level (a.s.l)
Foundation Elevation	1205.00 m above sea level (a.s.l)
Height from Bed Level	68 m
Total Volume of Concrete	1,492,000 m^3

2.3. Rainfall Data

There are four rainfall stations near the study area (Station Nos. 65, 82, 80, and 81). The rainfall data were recorded at rainfall gauge station 65. The details of rainfall stations are shown in Table 2, and the locations of these rainfall gauges are illustrated in Figure 5.

Table 2. Geographical location of the meteorological stations.

No.	**M. Station**	**Coordinates**		**Altitude (m)**	**Data Period**	**Region**
		Longitude (°) E	**Latitude (°) N**			
1.	Station 65	42°31′60.00″	19°51′60.00″	1607	1965–2018	Asir
2.	Station 82	42°48′0.00″	19°19′60.00″	1477	1965–2018	Asir
3.	Station 80	41°58′60.00″	19°27′60.00″	2249	1965–2018	Asir
4.	Station 81	41°55′60.00″	19°45′0.00″	1759	1965–2018	Asir

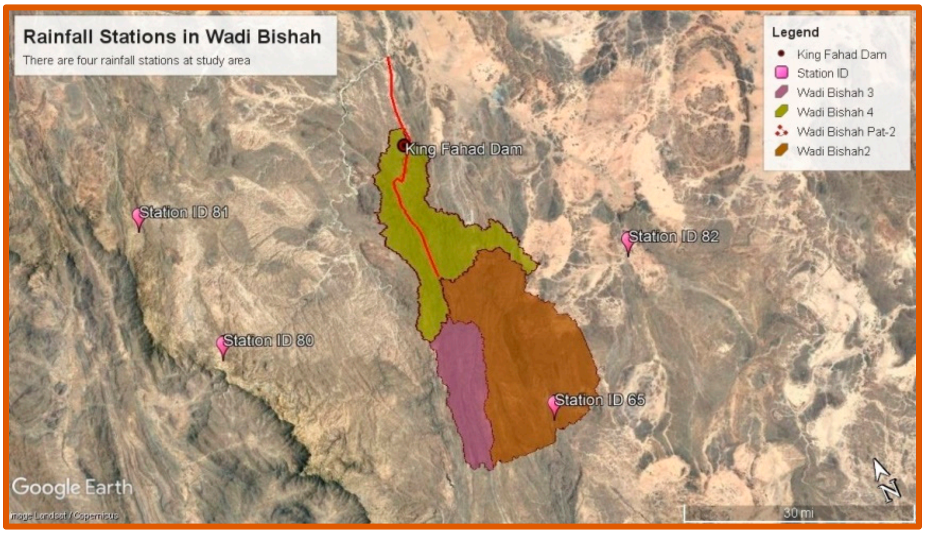

Figure 5. Meteorological stations in the study area.

The Wadi Bishah drainage basin area is characterized by arid and semi-arid conditions. The rainfall values of the catchment area of the Bishah dam were calculated using the rainfall data of the stations, as shown in Table 3, which lists the descriptive statistics of the daily maximum rainfall (DMR) (mm) for the (Wadi Bishah, M001) station using the Hyfran plus model.

Table 3. Basic statistics of rainfall data.

Basic Statistics of Rainfall Data	
No. of observations (year)	56
Minimum (mm)	0
Maximum (mm)	190.4
Average (mm)	64
Standard deviation (S.D) (mm)	50.7
Median (mm)	52.6
Coefficient of variation (Cv)	0.793
Skewness coefficient (Cs)	0.773
Kurtosis coefficient (Ck)	2.67

2.4. Proposed Location of Sediment-Trapping Basin

The purpose of a sediment trap basin is to facilitate the sedimentation process by reducing the velocity and turbulence of the river watercourse. It is crucial to select an optimum location for this trapping basin. An optimum site for a sedimentation basin depends on the flow velocity (minimum flow velocities) and satellite images (https://earthexplorer.usgs.gov/, accessed on 1 March 2022).

The following criteria should be considered to determine the location of a sediment-trapping basin in Wadi.

1. The sediment-trapping basin should be at a location that is easy for maintenance and cleaning works.
2. The sediment-trapping basin should be in an area with a large width to reduce the flow velocity.
3. Satellite images should be used to select an optimum location for the trapping basin.
4. The basin should be located in the mainstream to ensure that the sediments are collected from the minor streams.

USGS Maps (U.S. Geological Survey) were used in this study. Figure 6 shows several surveying locations of sediment-trapping basins upstream of the King Fahd Dam in Wadi

Bisha. The most appropriate location for the sediment-trapping basin was 16 km upstream of the King Fahd dam and 8 km upstream of the reservoir at the eastern branch. These sections had the largest cross-sectional area and minimum flow velocity, as shown in Figure 6.

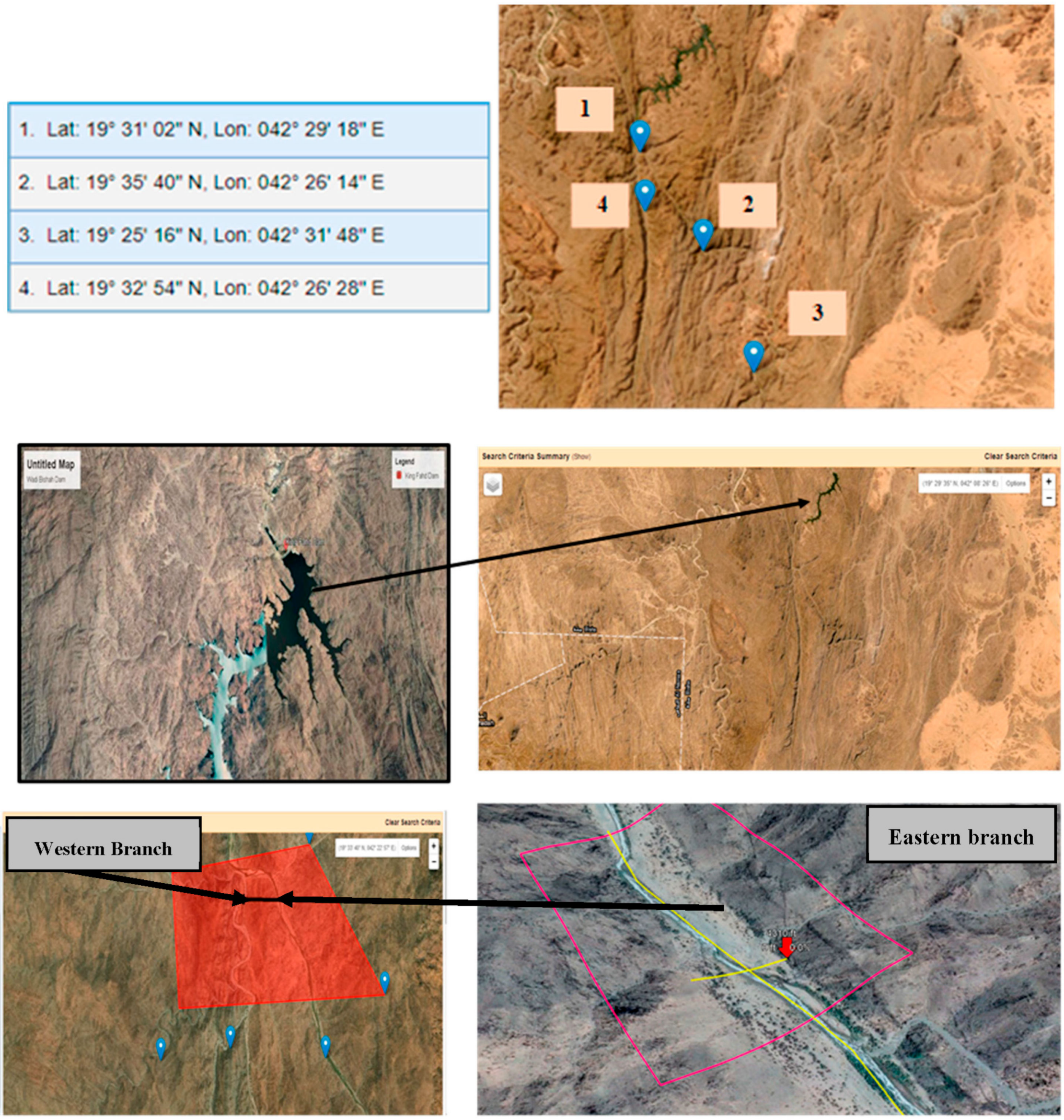

Figure 6. King Fahad Dam and the proposed sediment-trapping basin location (USGS).

2.5. *Chezy's Formula for Uniform Open-Channel Flow*

The several governing equations used in this study were Chezy's formula, which is probably the first formula derived for uniform and steady flow.

The Chezy equation for the flow is

$$\mathrm{V} = \mathrm{C}\sqrt{\mathrm{R.S}}, \tag{1}$$

$$\mathrm{R} = \frac{\mathrm{A}}{\mathrm{P}} \tag{2}$$

where V is the average velocity (m/s); R is the hydraulic radius equal to (A/P); S is the slope of the bed of the channel (m/km) (slope from section to section); and C is Chezy's coefficient of bed roughness.

A represents the area of water of the section m^2 and is calculated using Equation (3).

$$A = b\,y + z \cdot h^2 \quad (3)$$

P is the wetted perimeter of the section (m) and is expressed as

$$P = b + 2h \cdot \sqrt{1 + Z^2}, \quad (4)$$

where b is the bed width (m), y (= h) is the depth of water (m), and z is the side slope.

It was reported by Chow in 1959 that the side slope is 1:1 for soil with stone lining or earth for large channels, 3:2 for clay or soil for small ditches, and 2:1 for sandy soil [20].

2.6. Design Considerations of Trapping Basin Design

For the empirical design of the sediment-trapping basin, it is vital to define the main design criteria. It may include the following.

1. It is preferable to consider the bed load as 10–15% of the suspended load.
2. It is not required to trap fine particles, which are sediment particles smaller than 63 microns in size.
3. The sediment-trapping basins are designed to trap the majority of the particle sizes greater than 0.063 mm, which includes fine sand and coarser materials such as gravel.
4. Setting the minimum basin trap efficiency as 60–70%.
5. The ratio of the basin length\width is maintained in the range of 4–10 as recommended.
6. The fine particles such as silt and sand need to trap with the structure of a check dam.

2.6.1. Length of Settling Basin (L_b)

The sediment-trapping efficiency of the settling basins increases with an increase in the size of the sediment to be extracted. The volume of sediment extracted is primarily determined by the size of the sediment and the volume of discharge diverted through the basin [13].

Camp in 1946 presented a relationship that described the distance (L) a specific sediment particle of settling velocity U_s should travel [21].

The required distance (L_b) of a trapping basin should be defined using the following empirical equation:

$$\frac{h_u}{U_s} = \frac{L_b}{U_{av}} \quad (5)$$

where h_u is the upstream stream water depth (inlet of basin); L_b is the sediment settling basin length and U_{av} is the average flow velocity within the basin.

Us is assumed for ideal situations of medium silt particles, wherein fine silt and clay pass through the trapping basin and are deposited in the King Fahd Dam. The settling velocity of a sediment particle (mean diameter less than 0.10 mm) settling in water mixed with sediment can be determined using the approach of van Rijn (1987) as follows:

$$U_s = (1 - C)^{-\alpha} \frac{g d_s^2}{18\nu} \left(\frac{\gamma_s - \gamma_w}{\gamma_w} \right) \quad (6)$$

where U_s is the particle fall velocity in a mixed sediment-water (m/s); C is the mean sediment volume concentration (mg/L); d_s is the mean sediment particle diameter; a is a coefficient (a = 4–5 for particles in the range of 50–500 mm); γ_s is the specific weight of the sediment (γ_s =2.65 t/m^3); γ_w is the specific weight of water (γ_w = 62.4 lb/ft^3, 9810N/m^3); and υ is the kinematic viscosity of water (m^2/s) [22]. The kinematic viscosity is related to the temperature of water in the gravity canal as follows (van Rijn 1987):

$$\nu = 1.79^2 \times 10^{-6} \left(1 + 0.0337T + 0.000221T^2 \right) \quad (7)$$

2.6.2. Surface Area of Settling Basin (A_s)

The required surface area (A) of a perfect sediment-trapping basin should be defined through several formulas. Camp in 1946 proposed an equation to determine the area of the trapping basin as follows:

$$A_s = L_b \times L_b \ = \frac{Q}{U_s} \tag{8}$$

where A_s is the surface area of the trapping basin (m^2); L_b is the sediment-trapping basin length (m); W_b is the sediment-trapping basin width (m); Q is the flood discharge rate (m^3/s) corresponding to return period 10–100 years (peak).

2.6.3. Width of Surface Area of Trapping Basin (W_b)

Equation (9) can be used to evaluate the width of the settling basin water surface W_b for a trapezoidal stream.

$$W_b = W_{bottom} + 2.h_b \ .z \tag{9}$$

where h_b is the water depth within the trapping basin (m); h_b is the water depth selected primarily by the designer and represents the water height planned in the trapping basin; W_b is the sediment-trapping basin width; W_{bottom} is width at the bottom of the settling basin (m); and z is the slope of sides {(H: V, z = H/Z), (for 1:2, z = 2)}.

Equation (10) determines the basin width for the minimum length of the detention bsin (L_b)

$$W_b = \frac{A_s}{L_b} \tag{10}$$

2.6.4. Trapping Basin Storage Volume of Sediments (V_s)

Equation (11) shows that the quantities of sediment accumulated over three years are determined by the sediment loads entering the trapping basin, the portion of target sediment removed (R), and the settling velocity of sediment particles in the basin.

$$V_s = A_c \cdot R \cdot SYR \cdot F \tag{11}$$

where V_s is the volume of the sediment storage required (m^3); A_c is the contributing watershed area in km^2; R is the trap efficiency (%); TSL (SYR) is the sediment loading rate ($m^3/km^2/year$); and F is frequency in years.

2.6.5. Sediment-Trapping Efficiency and Sediment Particles Sizes

Elfiky in 2008 developed the following empirical relation to determine the percentage (%) of sediment trapped in the settling basin:

$$\xi_b = 1 - e^{-\frac{U_s \times A_s}{Q}} \tag{12}$$

where ξ_b is the sediment-trapping efficiency; U_s is the particle settling velocity in water (m/s); A_s is the surface area of the trapping basin (m^2); and Q is the flood rate (m^3/s).

3. Results of Hydraulic Design

The design of a debris basin is a three-step process. The first step is determining the critical sediment size or other critical aspects of the inflowing sediment load that should not be exceeded during the design event for the downstream conveyance system to function correctly. The second step is calculating the grain size distribution and volume of the inflowing load. The third step is determining the hydraulic characteristics of the basin required to trap the target grain size without trapping extremely fine material. A few researchers in 2016 had reported that sediment traps with open check dams are widely used structures for flood hazard mitigation. The main dimensions of the basin illustrated in Figure 7 are $L_b \times W_b \times d_s$. These dimensions are crucial as they significantly affect the trap efficiency [23].

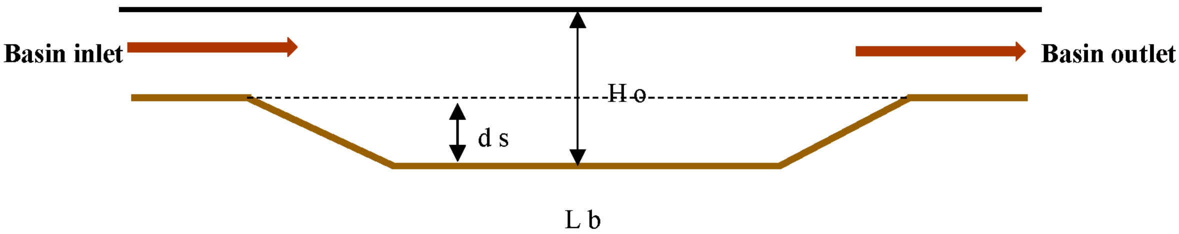

Figure 7. Longitudinal profile of the sediment-trapping basin.

3.1. Data Required for Sediment-Trapping Basin Design

In general, the data required for the design of the trapping basin can be grouped into three broad categories, geometric, hydraulic, and sediment data.

These data establish the boundary conditions required to solve empirical equations and proposed options. The data collection was analyzed and processed to fit the criteria of design.

(1). Geometric Data

The geometric data describe the cross-sections and longitudinal profile of the Wadi Bishah basin. The cross-section describes the area (A), depth (d, h), wetted perimeter (P), and hydraulic radius (R) of the natural stream (basin inlet). The longitudinal profile describes the slope of Wadi (S) near the basin, which is defined by a distance and elevation above a reference point (AMSL).

(2). Hydraulic Data

The hydraulic data include the upstream and downstream flood conditions. The flow velocity (v) and discharge (Q) are determined.

(3). Sediment Data Collected and Analysis

3.1.1. Sediment Data

Flow and sediment-transport data are analyzed and simulated to obtain the following.

- The flow duration curve (FDC).
- The sediment-rating curves (SRC).

The geometric data described the cross-section and longitudinal profile of Wadi Bishah near the inlet of the trapping basin. The digital elevation model (DEM) fitted the slope and the slope was determined as 10.6 m/km; see Figure 8.

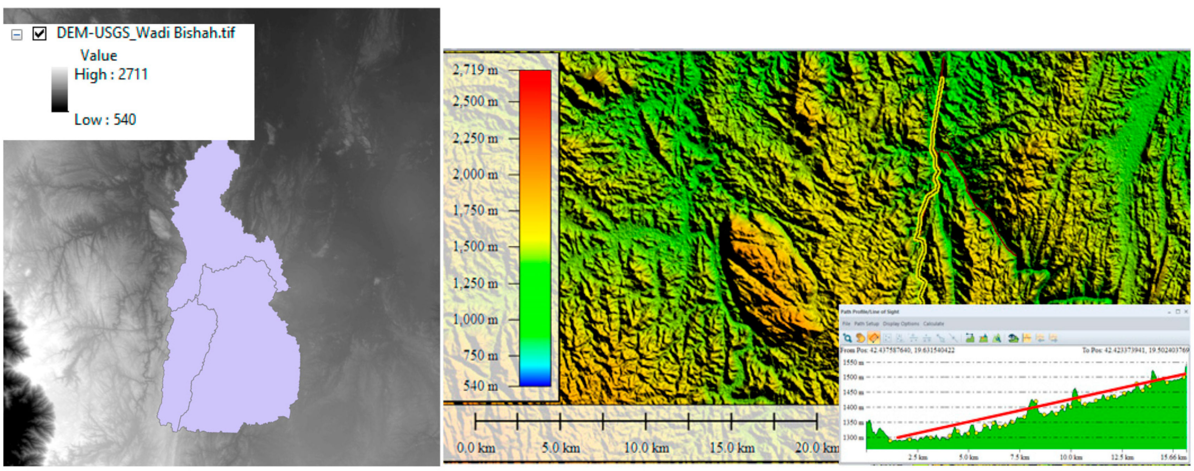

Figure 8. Longitudinal slope Global Mapper (DEM).

3.1.2. Hydraulic Data

A. Calculating the Flow Velocity

The minimum velocity of the Wadi Bishah trapping basin cross-section (inlet) is crucial to design the trapping basin. The shape of cross-sections was determined using Global Mapper-V24. A sample section was included to obtain the optimum hydraulic trapezoidal section for the basin with streamside slopes of 1:1. A velocity profile was used to determine the velocity for a cross-section.

The flow is uniform in the trapezoidal section of an open channel shown in Figure 9, considering all cross-sections as trapezoidal.

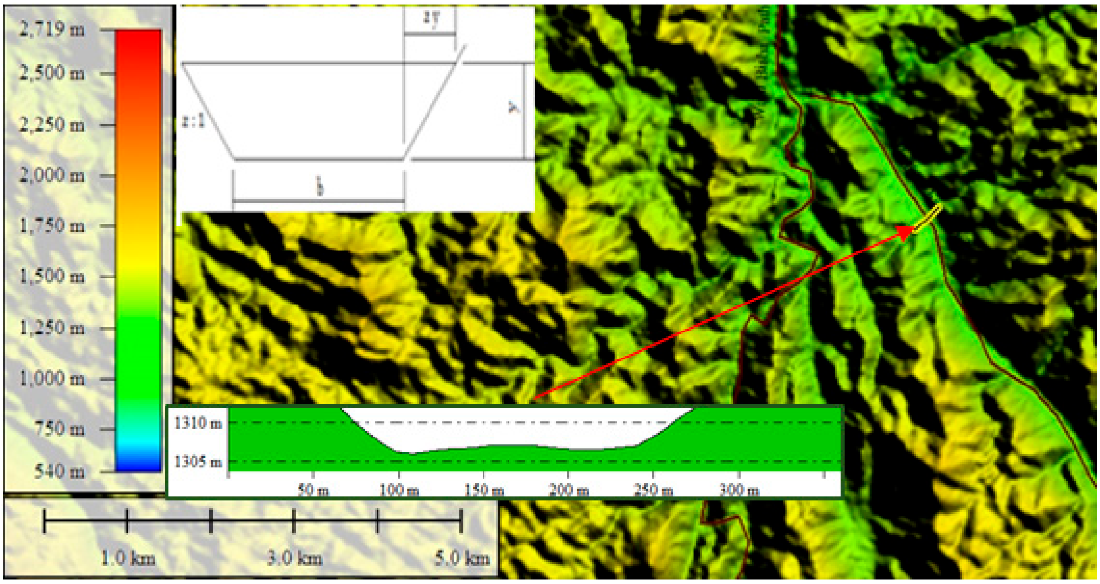

Figure 9. Cross-section of the inlet of the basin (obtained using Global Mapper-V24).

It was reported by Chow in 1959 that the side slope is 1:1 for soil with stone lining or earth for large channels, 3:2 for clay or soil for small ditches, and 2:1 for sandy soil [20].

Therefore, after substituting Equations (1)–(4) in the correct order (see Figure 9), we obtain the following equations.

$$h = 1\,314.3 - 1\,316.1 = 1.82 \ \approx 2\ \text{m}$$

$$A = b \times h + z\,h^2 = 76.65 \times 1.82 + 1 \times 1.82^2 = 142.8\ \text{m}^2$$

$$P = b + 2.h\,\sqrt{1 + Z^2} = 76.65 + \left(2 \times 1.82 \times \sqrt{1 + (1)^2}\right) = 81.8\ \text{m}$$

$$R = \frac{A}{P} = \frac{142.8}{81.8\ \text{m}} = 1.75\ \text{m}$$

Chezy's coefficient of bed depends on the assumptions about the Manning's roughness coefficient of the surface material of soil in the Wadi (an inlet of the basin→earth channel—gravelly) [24].

$$n = 0.025;\ C = \frac{R^{\frac{1}{6}}}{n} = 43.89$$

The slope of the channel bed is m/km (slope from section to section; see Figure 8).

$$S = \frac{d}{L} = \frac{(4301 - 4371)\text{ft}}{2.2\text{ mile}} = \frac{21,24}{3.54} = 6\ \text{m/km}\ = 6 \times 10^{-3}$$

The velocity obtained using Chezy's formula is as follows:

$$V = C \times \sqrt{R \times S} = 43.89 \times \sqrt{1.75 \times 6 \times 10^{-3}} = 4.49 \text{ m/s}$$

Therefore, a velocity of 4.49 m/s was used for the design. The geometric parameters according to the cross-section (inlet of basin) are slope 7.15×10^{-3} (m/m), channel bed-width 76.65 (m), area 142.8 (m^2), P 81.8 (m), R 1.75 (m), C 43.89, and velocity 4.49 (m/s); accordingly, the cross-sectional survey of the Wadi was performed.

B. Design Flows Wadi Bishah (Q_{design})

The discharge rate used for designing a water–sediment-trapping basin should fit the surface runoff conditions that are usually observed during the most frequent rainfall event, and a discharge rate of Q peak = 2688 m^3/s (MEWA,2020) was selected for this study show in Figure 10.

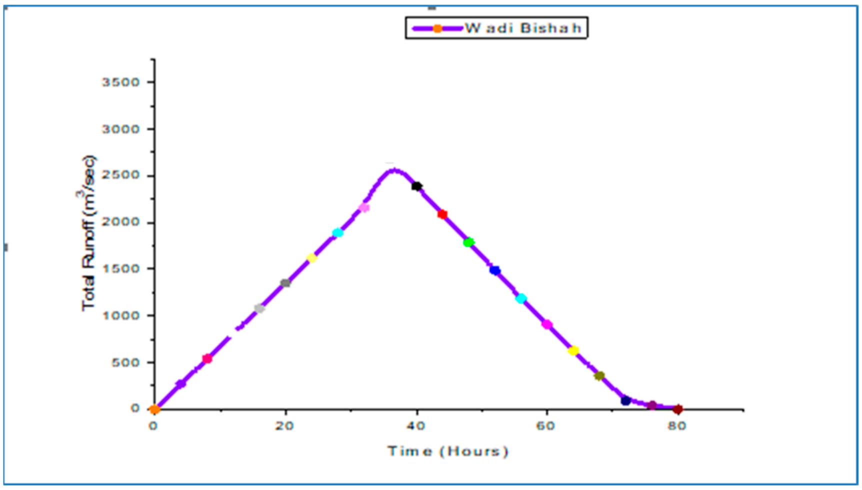

Figure 10. Wadi Bishah hydrograph (fitting with flow data).

3.1.3. Collection of Sediment Data and Analysis

The sedimentation measurements of Wadi Bishah in 1973 shown below in Table 4 adopted the maximum value of SSC [25].

Table 4. The concentration SSC mg/L as suspended measurements.

Station	Period Survey	Number of Measurements	Maximum of SSC (mg/L)
A-403, Hashbel	14.5.1973–14.6.1973	4	6700
A-402, Hashbel	29.4.1972–16.5.1973	32	29,400
A-406, Hashbel	15.3.1972–16.5.1973	22	86,800
SSC= 6700 mg/L			

A. Sediment Gradation:

The sediment particle size was defined using the Unified Soil Classification System (AGUS), as listed in Table 5. The maximum clay, silt, and sand sizes considered for the trapping basin design were 0.004, 0.0625, and 0.2 mm, respectively. These values are listed in Table 6.

Table 5. Particle size classification (AGUSCS).

Type of Sediment Materials	Description	Sediment Size Range (mm)
Gravel	Very coarse gravel	64–32
	Coarse gravel	32–16
	Medium gravel	16–8
	Fine gravel	8–4
	Very fine gravel	4–2
Sand	Very coarse sand	2.0–1.0
	Coarse sand	1.0–0.5
	Medium sand	0.5–0.25
	Fine sand	0.25–0.125
	Very fine sand	0.125–0.062
Silt	Coarse silt	0.062–0.031
	Medium silt	0.031–0.016
	Fine silt	0.016–0.008
	Very fine silt	0.008–0.004
Clay	Coarse clay	0.004–0.002
	Medium clay	0.002–0.001
	Fine clay	0.0010–0.0005
	Very fine clay	0.0005–0.00024

Table 6. Sediment gradation of trapping basin design.

Type of Sediment	Range of Grain Size (mm)			Percentage (%)	New Percentage (%)
	Upper Limit	Lower Limit	Average (d Average)		
Clay	0.004	0.002	0.003	20	30
Silt	0 062	0 031	0.03	10	
Fine sand	0.0625	0.25	0.13	30	70
Medium sand	0.25	0.5	0.375	10	
Coarse sand	1.0	0.5	0.75	10	
Fine gravel	8	4	6	20	
Medium gravel	16	8	12		
Coarse gravel	32	16	24		

B. Total Sediment Load Entering the Trapping Basin

Different techniques are used for estimating the total annual sediment load ($Q_T = Q_b + Q_s$). Several prediction methods have been reported for estimating total sediment load using suspended sediment concentration SSC and optimization approaches [6]. The annual average sediment load was 1823130.208 m^3/year, as listed in Tables 7 and 8.

Table 7. Suspended-sediment discharge (SSD) for Wadi Bishah.

	Ray 1	Ray 2	Ray 3	Ray 4	Ray 5	Ray 6
	% Time Increment	Time Increment	Average of Time Increment	Daily Flow (Q_{flow})	D.S.F (Q_s)	S.S.D for Time Increment
	%	Δ%	%	m^3/s	Ton/day	Ton
1.	0.02	0.02	0.01	0	0	0
2.	0.1	0.08	0.06	270	155,574	124.4592
3.	0.2	0.10	0.15	540	311,148	311.148
4.	0.5	0.30	0.40	810	466,722	1400.166
5.	1.0	0. 5	0.75	1080	622,296	3111.48
6.	2.0	1.0	1.5	1350	777,870	7778.7
7.	3.0	1.0	2.5	1620	933,444	9334.44
8.	5.0	2.0	4.0	1890	1,089,018	21,780.36
9.	9.0	4.0	7.0	2160	1,244,592	49,783.68
10.	15.0	6.0	12.0	2688	1,548,825.6	92,929.536
11.	25.0	10.0	20.0	2388	1,375,965.6	137,596.56
12.	35.0	10.0	30.0	2088	1,203,105.6	120,310.56
13.	45.0	10.0	40.0	1788	1,030,245.6	103,024.56
14.	55.0	10.0	50.0	1488	857,385.6	85,738.56
15.	65.0	10.0	60.0	1188	684,525.6	68,452.56
16.	75.0	10.0	70.0	908	523,189.6	52,318.96
17.	85.0	10.0	80.0	628	361,853.6	36,185.36
18.	95.0	10.0	90.0	358	206,279.6	20,627.96
19.	99.0	4.0	97.5	90	51,858	2074.32
20.	99.8	0.8	99.4	40	23,048	184.384
	Total	99.8	-	-	-	813,067.7532

- Average daily suspended sediment load: 813,067.7532 Tons/day Total annual suspended sediment load: (813,067.7532 × 60 day/year) = 3,252,271.013 Ton/Year, 1,519,275.173 m^3/year
- The total sediment load was estimated based in that period because the flood period occurs within two months of the year.

The scenarios below related to the flood period, which occurs (365,120,60 days) of the year. The 3 Scenario 3-3 was selected because it was reflective of the historical data of Wadi Bishah watershed sediment yield, which is (SYR 1973 =192 m^3/year/km^2→1,459,200 m^3/year) (MOWE, 1973). Ministry of Water and Electricity.

Scenario-1-1		Qs = Ton/year 296769729.9	Qs = m3/year 138633859.5
Scenario-1-2		Qs = Ton/year 97568130.38	Qs = m3/year 45578255.19
Scenario-3-3		Qs = Ton/year 3252271.013	Qs = m3/year 1519275.173
Qbed	303855.0346		
Qtotal	1823130.208		

The annual total sediment load in m^3/year at the entrance to the trapping basin, including suspended and bed sediment loads, is 1,519,275.173 + 303,855.0346 = 1,823,130.208 m^3/year.

Table 8 lists the magnitudes of the total sediment load estimated according to the grain size analysis of Wadi Bishah.

Table 8. Annual quantities of sediment expected to enter the trapping basin.

Type of Sediment	Particle size (ds)	Percentage (m)	Annual Quantities (Ton/Year)	Rate (m^3/km^2/year)	Trap Efficiency ® (%)
Clay	0.003	20	364,626.0416	47.977	30%→71.966
Silt	0.03	10	182,313.0208	23.989	
Fine sand	0.13	30	546,939.0624	71.966	70%→167.921
Medium sand	0.5	10	182,313.0208	23.989	
Coarse sand	1	10	182,313.0208	23.989	
Fine gravel	6	20	364,626.0416	47.977	
Total		100%	1,823,130.208	239.887	71.966 + 71.966

Table 8 shows that the trap efficiency R(%) for the clay and silt was 30%→ 71.966 m^3/km^2/year, and that for the coarse material was 70%→167.921; therefore, R was assumed in the range of 60–70% for the estimation of the trapping basin volume (Vs).

3.2. Hydraulic Design of Sediment-Trapping Basin

A sediment-trapping basin was designed to reduce the sediment particles flowing through Wadi Bishah to King Fahd Dam. This study used theoretical and empirical equations to determine the minimum volume of the trapping basin required to trap sediments. Parameters such as the length of the settling basin (L_b), settling velocity of the sediment particle (U_s), surface area of the settling basin (As), and width of the surface area of the settling basin (W_b) were used.

A. Length of Settling Basin (L_b):

Us is assumed for ideal situations of medium silt particles, wherein fine silt and clay pass through the trapping basin and are deposited in the King Fahd Dam, where $U_{av} = 4$ m/s and U_s= is the sediment particle settling velocity (=0.0023).

Here, h_u is the upstream stream water depth (inlet of basin). It can be observed from Equation (5) that $h_u = 2$ m L_b is the sediment settling basin length and U_{av}= is the average flow velocity within the basin.

The equation below is an empirical formula adopted by Camp in 1946. It describes the distance (L_b) traveled by a specific sediment particle for a settling velocity Us [21].

$$\frac{2}{0.0023} = \frac{L_b}{4} \rightarrow L_b = 3478.3 \text{ m} \approx 3500 \text{ m}$$

B. Surface Area of Settling Basin (A_s)

$$A_s = \frac{Q}{U_s} = \frac{2688}{0.0023} = 1168695.6 \text{ m}^2$$

C. Width of Surface Area of Trapping Basin (W_b)

To determine the basin width for the minimum length of the detention basin (L_b)

$$W_b = \frac{A_s}{L_b} = \frac{1168695.6}{3500} = 333.913 \approx 500\text{m}$$

$$A_s = W_b \times L_b = 500 \times 3500 = 1750000 \text{ m}^2$$

Table 9 lists the trapping basin parameters of the Wadi.

Table 9. Main dimensions and parameters for Wadi Bishah trapping basin related to coarse silt.

Particle Type	**D (mm)**	**U_s (m/s)**	**Time**	**U_{ent} (m/s)**	**L_b (m)**	**A_S (m)**	**W_b (m)**	**A_{inflow} (m^2)**
Coarse silt	0.062	0.0023	9 min	0.11	4007.6	1,418,696	333	752.25
Description	**L_b(m)**	**W_b(m)**	**Area(m^2)**	**Q Peak (m^3/s)**		**Design Velocity (m/sec)**		**h_s(m)**
Basin	3500	500	1,750,000	2688		4		1.5

A rectangle shape with an L_b/W_b ratio greater than 2 is recommended to increase the trap efficiency in the basin while designing a trapping basin. The basin parameters are provided in Table 9 and Figure 11.

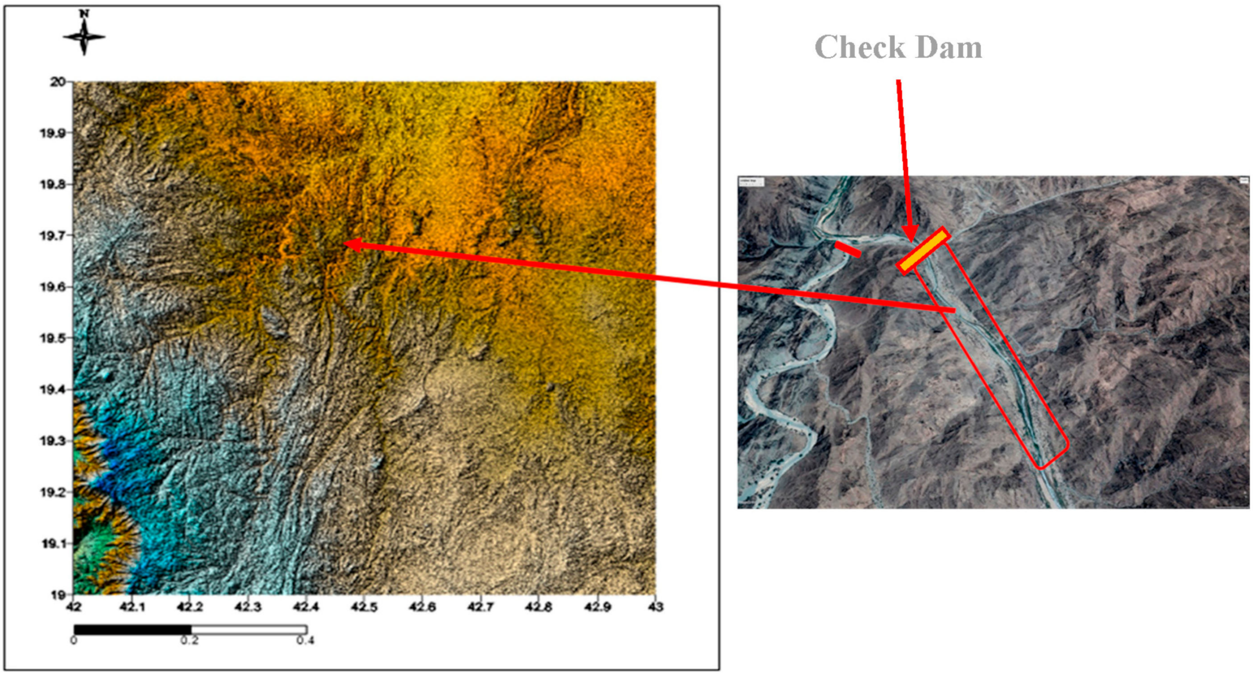

Figure 11. Definition plan of the proposed trapping basin.

D. Minimum Depth of Trapping Basin (h_s)

It is necessary to prevent the re-suspension of sediment particles once they have settled to the bed of the trapping basin. This is performed by lowering the flow velocity near the bed basin (tangential velocity, v_{tan}) to a level lower than that of the velocity at which sediment particle re-suspension occurs (entrainment velocity, Uent). Sufficient flow depth and flow area should be maintained in the trapping basin during frequent rainfall events to achieve this objective. Figure 12 depicts these velocities.

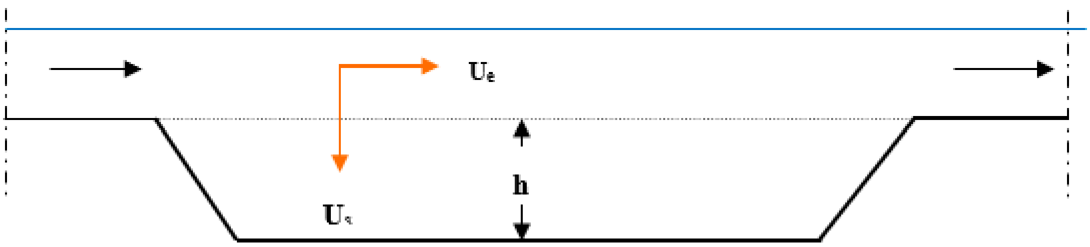

Figure 12. Depth, entrainment velocity (Uent), and settling velocity (Us) in the basin section.

E. Trapping Basin Storage Volume of Sediments (V_s)

The provision of sufficient storage for settled sediment to prevent the requirement for frequent desilting is a consideration during the design of a settling basin. The settling basin storage volume (V_s) should be greater than that of the volume of the accumulated sediment over the desired desilting years. The optimum frequency of desilting the settling basin is at intervals of three years. The quantities of sediment TSL (SYR) accumulated over three years are determined with the trap efficiency (R %) assumed as 60–70%. The Wadi Bishah watershed area (7600 km^2) sediment yield rate S·Y·R shown in Table 8 is 167.921 ($m^3/km^2/year$). The trap efficiency (%) is assumed as 60–70%, the frequency varies each year. Equation (17) is used to estimate sediment storage volume in the sediment-trapping basin. Equation (17) and Table 8: $V_{3years} = 2.4 \times 10^6$ m^3, $V_b = 2.6 \times 10^6$ m^3. Therefore, the basin storage volume (V_b) is sufficient for the accumulated sediment over three years. The maintenance and cleaning of the deposits trapped in the basin should be performed at an interval of three years.

4. Discussions

Sediment-trapping basins provide a feasible solution to the problems of siltation, which is important to reservoir life; one of the important results of this study tries to create a new concept to trap sediment in wadis in arid and semi-arid regions. This study provides a proposal of sediment-trapping basins to trap sediments that helps to effectively manage and control sediment in reservoirs. This option of sediment control and trap is a feasible solution for reaching the optimal design of dams located on steep slope areas such as Wadi Bishah in the south of Saudi Arabia. The sediment-trapping basin is one of the mitigation measures that can be taken in order to reduce the amount of sediment inflow (watershed rehabilitation as structural measures). Sediment-trapping basins do not prevent erosion; they trap eroded watershed soil before it can arrive at dams. Therefore, it is of course far better to prevent erosion than it is to trap sediment from eroded areas. The sediment-settling basin is selected in this study because other procedures such as vegetation are not feasible. Sediment trapping is only a temporary measure unless it is combined with sediment removal, and sediment removal from the reservoir would probably be materially more difficult and costly than removal from detention basins. Sediment traps with open check dams are widely used structures for flood hazard mitigation. Sediment-trapping basins are built with sufficient sediment load storage capacity to ensure sediment removal at an interval of three years. The trapping basin must be emptied after seasonal flood events (in the period of drought Wadi Bishah). The best periods for desilting work are October to the first of December and from March to April. The optimum settling basin dimensions are $L_b \times W_b \times hs = 3500 \times 500 \times 1.5$ m. Also, for these dimensions, the basin efficiency was assumed to be in the range of 60–70%. For these dimensions, the detention basin should be enough to receive about 30% of the suspended sediment load, and all the sediment of sizes larger than 0.03 mm should be trapped in the settling basin with a basin trap efficiency of 60–70%. The relationship between the settling velocity U_S of sediment entering the basin and basin length L_b indicated that the minimum values of settling velocity increase the length of the sediment-trapping basin and thus increases the detention time (and hence trap efficiency, R). The relationship between basin areas As and values of settling velocity US for medium sand, fine sand, medium silt and clay with sediment trap efficiency of 60–70% indicated that the minimum values of settling velocity increase the surface area of the settling basin and thus increases the detention time (and hence trap efficiency, R). Finally, for more efficiency, it is recommended to construct sediment traps with open check dams, which are widely used structures for flood hazard mitigation. Sediment-trapping basins are built with sufficient sediment load storage capacity to ensure sediment removal at an interval of three years. Open check dams should be constructed upstream of the trap basin to enhance the efficiency of the sediment-trapping basin. The Wadi Bishah trapping basin should be emptied (during the period of drought in Wadi Bishah) following seasonal flood events.

5. Conclusions

The optimum sediment-trapping basin dimensions were $L_b \times W_b \times h_s$= 3500 × 500 × 1.5 m. The optimum location for a sediment-trapping basin was 16 km upstream of the King Fahd Dam and 8 km from the end of the lake at the western branch. These sections had the largest cross-sectional area and minimum flow velocity. The trap efficiency of the basin was estimated to be in the range of 60–70% because sediments, except clay and fine silt (40–30%), were trapped. Sediment particles of sizes larger than 0.03 mm should settled and be trapped in the sediment-trapping basin with a basin trap efficiency of 60%. A check dam with spillway gates should be constructed at the basin outlet with a height of 2 m and width of 500 m to increase the trap efficiency of the sediment-trapping basin. The Wadi Bishah trapping basin should be emptied after seasonal flood events (in the period of drought).

Author Contributions: Conceptualization, A.T.B.T. and A.A.; methodology, A.T.B.T. and A.M.A.M.; formal analysis, A.T.B.T.; investigation, A.T.B.T. and A.M.A.M.; resources, A.A.; data curation, A.T.B.T. and A.A.; writing—original draft preparation, A.T.B.T. and A.A.; writing—review and editing, A.T.B.T. and A.M.A.M.; supervision, A.M.A.M.; funding acquisition, A.T.B.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data can be made available upon reasonable request.

Acknowledgments: The authors gratefully acknowledge that: "This study is supported via funding from Prince Sattam bin Abdulaziz University, project number (PSAU/2023/R/1444)".

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

WCD	World Commission on Dams
GIS	Geographical Information System
U/S	Upstream
D/S	Downstream
SRH-1D	Sedimentation and River Hydraulics—One Dimension
CCHE2D	Center for Computational Hydro science and Engineering Two Dimension
MOEAW	Ministry of Water, Environment and Agriculture
USGS	United States Geological Survey
DEM	Digital Elevation Model
DMR	Daily Maximum Rainfall
AMSL	Above Mean Sea Level
FDC	Flow Duration Curve
SRC	Sediment-Rating Curves
AGUS	Unified Soil Classification System
MOWE	Ministry of Water and Electricity
DSF	Daily Suspended Flow
SSD	Daily Suspended Sediment
SL	Suspended load
BL	Bed Load
BM	Bed Material Load
TSS	Total Suspended Solids
SSC	Suspended Sediment Concentration
FISP	Federal Interagency Sedimentation Project
NTU	Nephelometric Turbidity Unit

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