

ENVIRONMENTAL ASSESSMENT OF THE AUXILIARY KANDAR DAM AND ITS INFLUENCE ON THE LIFESPAN EXTENSION OF THE MAIN RESERVOIR: EVIDENCE FROM KOHAT, PAKISTAN

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Background: Reservoir sedimentation poses a significant challenge to water resource sustainability, as it reduces storage capacity, compromises hydraulic performance, and shortens the operational lifespan of dams. In Pakistan, many reservoirs face accelerated sediment accumulation due to steep catchment slopes and intensive land use, yet limited research has focused on the role of auxiliary dams in mitigating these effects. **Objectives:** This study aimed to assess the environmental impact of the Auxiliary Kandar Dam on extending the lifespan of the Main Reservoir in District Kohat, Khyber Pakhtunkhwa. It sought to quantify sediment deposition, evaluate trapping efficiencies, and model future storage scenarios under different auxiliary dam construction timelines. The research addressed a key knowledge gap regarding how auxiliary dam construction can optimize sediment retention and improve reservoir sustainability in semi-arid regions. **Methods:** A detailed grid survey was conducted to determine the storage capacities of both reservoirs, with volumetric and spatial analyses performed using SURFER software. Sediment yield estimations were calculated through the HR Wallingford Sediment Yield Prediction Model (WSYPM). Field observations, hydrological data, and chronological sediment records were integrated to validate trapping efficiencies and predict future capacity loss scenarios. **Results:** The initial capacities of the Main and Auxiliary Dams were 1,000,365 m³ and 1,994,974 m³, respectively. Over nine years, the Auxiliary Dam accumulated 196,654 m³ of sediment, resulting in a 9% loss in storage capacity. The Main Dam exhibited a trapping efficiency of 90.48%, which declined with a decreasing inflow ratio from 0.508 to 0.194. Within six years, approximately 175,501 m³ of sediment were deposited in the Main Dam, causing a 61.78% reduction in total storage capacity over 41 years. The observed sedimentation patterns closely matched WSYPM predictions. Importantly, the construction of the Auxiliary Dam in 2014 extended the Main Dam's effective lifespan by 34 years (2022 – 2056). Modelling suggested that additional auxiliary structures in 2016 or 2022 could further prolong the lifespan by 80 years (2022 – 2102) or 68 years (2022 – 2090), respectively, while a proposed left Auxiliary Dam (2025) would extend it by 66 years (2022 – 2088), yielding an overall operational duration of 107 years (1972 – 2079). **Conclusion:** The findings confirm that the construction of the Auxiliary Kandar Dam significantly reduced sediment inflow into the Main Reservoir, effectively extending its operational lifespan and ensuring sustainable water storage for the region. The study successfully demonstrates, for the first time in this geographic context, the quantitative relationship between auxiliary dam placement and sediment reduction efficiency.

Keywords: dam; water resources management; sedimentation rate; storage capacity; sediment load; sustainable water storage; semi-arid regions; SDG 6.

INTRODUCTION

Water is the most crucial gift bestowed by nature, vital for the survival of all living beings, including humans. Its importance in agriculture is profound, as agricultural productivity depends heavily on water availability and efficient usage (Shah & Wu, 2019). Pakistan, an agricultural country endowed with fertile land, relies extensively on its water resources (Kamal et al., 2022). Out of its approximately 79.6 million hectares of geographical area, only 27% is currently under cultivation. The country hosts one of the world's largest irrigation systems (Saleem & Shrestha, 2019) and has the highest proportion of irrigated crop area globally (Kirby et al., 2017). However, poor management of irrigation systems has resulted in low crop yield response per unit of water, causing significant agricultural losses (Minhas et al., 2020). Small surface reservoirs play a vital role in addressing these challenges by serving as buffers during dry spells and droughts. They provide essential water resources to rural communities for multiple uses, including irrigation, livestock watering, construction, and aquaculture (Leader & Wijnen, 2018).

Reservoir sedimentation poses a significant challenge to sustainable management, involving the transport of eroded soil material by runoff (Bhatti et al., 2021). Erosion from catchment areas leads to a rapid decline in reservoir storage capacity, diminishing their economic lifespan (Zarfl & Lucía, 2018).

The increasing sediment rates are primarily responsible for the reduction in reservoir storage capacity (Gonzalez Rodriguez et al., 2023). Sedimentation rates present a global concern for reservoir operation and water management, especially in semi-arid regions (Emamgholizadeh et al., 2018). The utilization of mathematical modelling, such as HEC-RAS, offers viable approaches for remediation and prevention of sedimentation, thus extending the useful life of dams (Beebo & Bilal, 2012). Sedimentation processes are influenced by both natural factors and human activities (Wu et al., 2021). Therefore, there is a pressing need to develop cost-effective methods for assessing sedimentation in reservoirs (Shrestha et al., 2021).

The wavelet artificial neural network (WANN) model emerged as the most accurate predictor for suspended sediment load (SSL) (Zeyneb et al., 2022). Mohammad et al. (2020) demonstrated through the Sediment Simulation in Intakes with Multi-block option (SSIIM) model how sediment distribution reflects changes in bed level and water levels. Soil erosion, influenced by sediment load and drainage areas, poses significant environmental and societal challenges. Jameel et al. (2022) illustrated that the sediment trapping efficiency, as depicted by the trap efficiency curve, approaches 100% within a specific data range. Nahib et al. (2024) emphasized that erosion depends upon various factors, including soil type, topography, vegetation cover, climate, and land use. Large sediment transport into reservoirs is primarily attributed to

high-intensity rainfall events (Gonzalez Rodriguez et al., 2023). Accelerated erosion for rainfall has been observed during the season when soils are bare and unprotected (De Crop et al., 2023). Moreover, Mugizi & Matsumoto (2020) highlighted the correlation between population growth and intensified agriculture, which exacerbates soil erosion due to increased pressure on the land.

Inappropriate land use and human-induced changes in land cover significantly impact sediment transport (Leta et al., 2017). Effective planning and sustainable management of water resources are crucial in semi-arid regions like Pakistan, necessitating the evaluation of reservoir capacities and sedimentation rates (Ishaque et al., 2023).

This study was conducted from 2021 to 2023 to evaluate capacity loss caused by sedimentation and to compare projected sediment rates by Wallingford, H. R with observed data. The purpose of this study was to advance the scientific understanding of sediment dynamics in small reservoir systems by quantifying and modelling sedimentation processes affecting dam longevity. Specifically, the study attempt to determine how the construction of the Auxiliary Kandar Dam influences sediment load reduction and lifespan extension of the main Kandar Reservoir. Despite extensive global research on reservoir sedimentation, limited studies have explored the functional interdependence between primary and auxiliary dams under semi-arid conditions such as those in northern Pakistan. This study addresses this knowledge gap by integrating field-based sediment sampling with hydrological modelling to estimate annual sediment loads in both reservoirs, compare model-predicted sediment yields (using the Wallingford, H. R. method) with observed data, and evaluate temporal changes in reservoir storage capacity. The central hypothesis is that the Auxiliary Kandar Dam significantly reduces downstream sediment inflow, thereby enhancing the operational lifespan of the main reservoir.

MATERIALS AND METHODS

Study area

The study was conducted at Kandar Dam, which is a significant water reservoir located in the Kohat District of Khyber Pakhtunkhwa, Pakistan. It plays a crucial role in water resources management and irrigation in the region. Kandar Dam, constructed to address the water needs of the area, serves multiple purposes, including water storage, flood control, and agricultural irrigation. The dam is strategically situated between latitude $33^{\circ}33'45.40''$ N and longitude $71^{\circ}50'44.25''$ E, covering a catchment area of 27.9 square miles (Figure 1). With a cultivable command area (CCA) spanning 2038 acres, it provides essential irrigation water to the surrounding agricultural lands. The construction of Kandar Dam has greatly contributed to the socio-economic development of the region by enhancing agricultural productivity and ensuring water availability for domestic and industrial purposes. Additionally, it serves as a recreational spot for residents and tourists, attracting visitors with its scenic beauty and tranquil surroundings.

The climatic conditions in the vicinity of Kandar Dam are characterized as arid to semi-arid, with mean annual precipitation ranging from 300 to 450 mm. Despite challenges such as sedimentation and water loss, the dam continues to play a vital role in water management and irrigation, contributing to the overall prosperity of the Kohat District and its surrounding areas.

Data collection

Primary data for this study were collected directly from the field between August 2022 and September 2023 in the Shakardara District, Kohat, Pakistan.

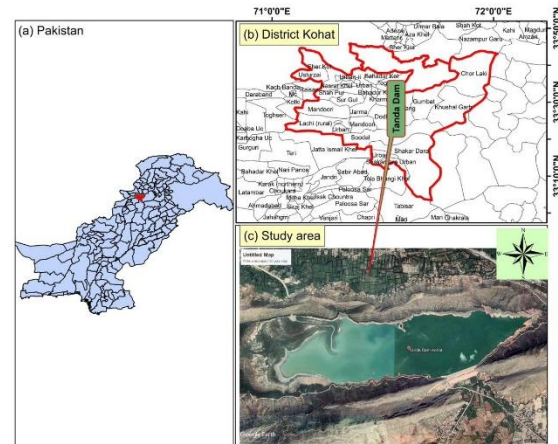


Figure 1. Map of study area showing sampling sites

The parameters recorded included reservoir capacity, dam height, spillway location, embankment length, soil type, and percentage of vegetative cover. Field surveys were conducted using GPS mapping and manual measurement tools to ensure spatial accuracy. Additionally, hydrological and topographical data, including rainfall patterns, sediment load, land use, and ground cover, were obtained from the Pakistan Meteorological Department (PMD), the Water and Power Development Authority (WAPDA), and the Geological Survey of Pakistan (GSP).

To assess sedimentation, a systematic grid survey was performed in nine embankment reservoirs, including the main and auxiliary Kandar Dams. The reservoir areas were divided into grids measuring $20\text{ m} \times 5\text{ m}$, and depth measurements were taken at each grid point using a calibrated echo sounder and sediment probe. Sediment samples were collected from selected points for laboratory analysis of texture and density to estimate sediment deposition rates. The spatial distribution of sediment accumulation was processed using ArcGIS 10.8, and contour maps were generated to visualize the sedimentation pattern (Figure 2).

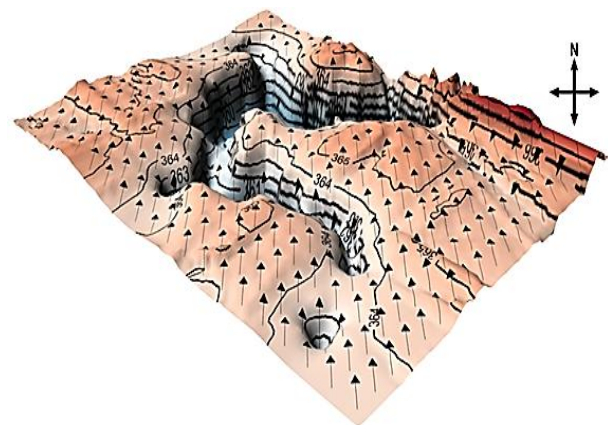


Figure 2. Contour map of the Main Kandar Dam generated from field survey data

Determination of deposited sediment load and storage capacity

The deposited sediment load in the reservoirs of the Auxiliary Kandar Dam and Main Kandar Dam was quantified by comparing the present storage capacity with the previously documented reservoir volumes recorded at the time of dam commissioning. To determine the current storage capacity, a detailed bathymetric grid survey was conducted in which the

entire reservoir surface was systematically divided into uniform 20 m × 20 m grid cells. At each grid point, the geographic coordinates (latitude and longitude) were recorded using a handheld GPS unit (Garmin GPSMAP 64sx), while water depth was measured using a portable echo sounder (Hondex PS-7). The grid points were accessed by boat, and depth measurements were taken vertically from the water surface using the echo sounder's transducer (Figure 3).

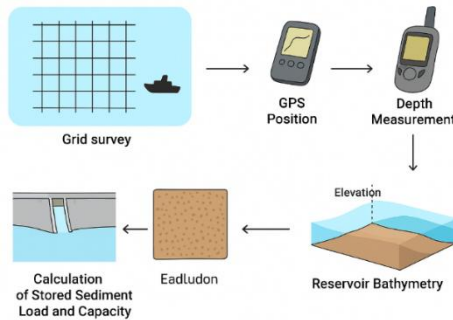


Figure 3. Workflow for sediment survey and storage capacity assessment

The measured water depth at each grid point was then converted into a below-water earth-surface elevation by subtracting the recorded depth from the contemporaneous water surface elevation, which was measured using an automatic water level gauge installed on the spillway wall. This process produced a set of three-dimensional data points (latitude, longitude, and computed bed elevation), allowing a detailed reconstruction of the current reservoir bathymetry. All elevation-referenced grid data were subsequently imported into Surfer 15, where a digital elevation model (DEM) of the reservoir bed was generated using kriging interpolation. The DEM was then used to calculate the present reservoir storage capacity by integrating all volume values up to the spillway crest elevation, and the difference between this calculated volume and the previously recorded design capacity was interpreted as the total accumulated sediment load.

Annual sediment rate

The annual sediment rate and total sediment transport were estimated by comparing the observed reservoir storage (measured during the bathymetric survey) with the historical design storage reported by the Government of Khyber Pakhtunkhwa (KP). The original storage capacities, catchment areas, and design hydrological parameters for both the Auxiliary Kandar Dam and the Main Kandar Dam were obtained from official feasibility and design reports available through the Irrigation Department, Government of Khyber Pakhtunkhwa.

Bathymetric and sediment–depth measurements used to derive the current reservoir storage were collected directly by the authors using a grid-based field survey (20 m × 5 m resolution). Using these two datasets (design vs. observed storage), the annual sediment deposition rate for both dams was calculated using the following equations:

$$AST \left(\frac{m^3}{year} \right) = \frac{\text{Total sediment volume (m}^3\text{)}}{\text{Number of Years}}, \quad (1)$$

where AST is annual sediment transport.

The sediment yield rate normalized by catchment area was estimated as:

$$\text{Sediment rate} \left(\frac{m^3}{km^2 \cdot year} \right) = \frac{AST \left(\frac{m^3}{year} \right)}{\text{catchment area (km}^2\text{)}}. \quad (2)$$

All hydrological and structural baseline data used for these calculations were obtained from the KP Irrigation Department's publicly accessible dam records, while all updated storage and sedimentation data were generated during field surveys.

Wallingford sediment yield prediction model (WSYPM)

The Wallingford model was used to predict sediment yield by collecting data on various factors such as catchment area, annual rainfall, slope, and quantitative descriptors of soil and vegetative cover, as well as evidence of accelerated erosion. Additionally, qualitative observations including Signs of Active Soil Erosion (SASE), Soil Type and Drainage (STD), and Vegetation Cover (VC) were recorded to provide inputs for the HR Walling Model, particularly for specific dam waterways and other catchment characteristics.

Long-term rainfall analysis and annual variability

Long-term rainfall patterns were evaluated using 50 years of daily precipitation data (January 1971 – December 2020) obtained from the Pakistan Meteorological Department (PMD). The complete dataset used in this analysis is shown in Table S1 (supplementary materials) for transparency and verification. Before analysis, the raw data were screened for missing values, inconsistencies, and outliers following PMD quality-control standards.

Annual rainfall totals were computed by aggregating daily precipitation values for each calendar year. These annual totals were then compared against the long-term mean (1971 – 2020) to assess inter-annual variability and potential trends in precipitation that may influence sediment inflow and reservoir operation. Figure 4 indicated the year-to-year variations in total rainfall relative to the long-term average, enabling a clear visualization of wet and dry periods over the 50-year record.

Assessment of slope

The slope of the catchment areas surrounding the Auxiliary Kandar Dam and the Main Kandar Dam was assessed through a combination of field measurements and geospatial analysis. A longitudinal survey was conducted along each waterway using a dumpy level to establish elevation differences between the upstream origin in the upland zone and the downstream outlet at the reservoir. To further characterize slope variations, three cross-sections (at the head, middle, and tail reaches) were surveyed using the dumpy level to determine lateral elevation changes and to evaluate runoff behaviour under peak-flow conditions.

A detailed cross-profile was also recorded from the mountain crest to the base of the waterway to capture secondary slopes that contribute to the overall gradient. These field measurements were validated using Digital Elevation Models (DEMs) derived from the Shuttle Radar Topography Mission (SRTM) dataset and high-resolution Google Earth imagery. Elevation extremes within the catchment were identified using handheld GPS measurements. The catchment slope was calculated using the following standard expression:

$$\text{Slope} = \frac{\text{Elevation difference}}{\text{Horizontal catchment length}}. \quad (3)$$

All elevation data used for validation were obtained from the SRTM 1-Arc-Second Global DEM, which is publicly available through the USGS EarthExplorer platform (<https://earthexplorer.usgs.gov>), while additional elevation verification and terrain visualization were carried out using Google Earth imagery (<https://earth.google.com>).

Estimation of life of the dam

The lifespan of the Main Kandar Dam reservoir, both before and after the construction of the Auxiliary Kandar Dam, was estimated using the total annual sediment yield and the available storage capacity of the reservoir.

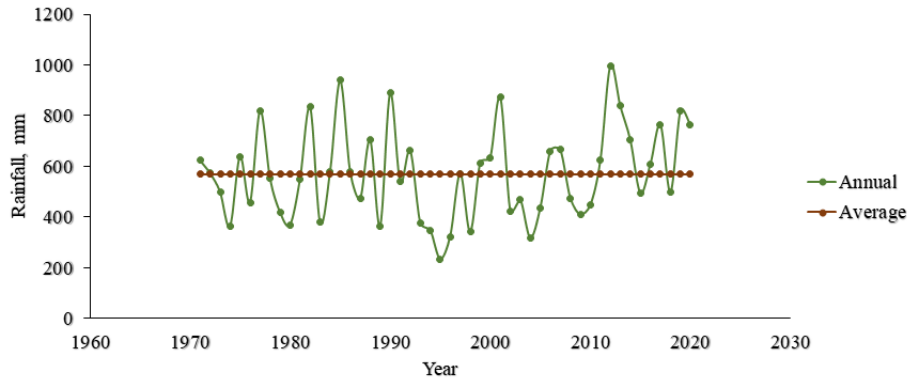


Figure 4. Plot of annual rainfall data for the study area

Annual sedimentation rates and the corresponding storage capacities of the dam were computed using the Surfer software. The effective operational life of the reservoir was then determined using given equation:

$$\text{Effective life (years)} = \frac{\text{ARC (m}^3\text{)}}{\text{Annual Sediment rate}(\frac{\text{m}^3}{\text{year}})}, \quad (4)$$

where ARC is available reservoir capacity.

RESULTS

Storage capacity of Kandar and Auxiliary Kandar Dam

The stage capacity relationship typically illustrates how the storage capacity of a reservoir changes with variations in water level or stage. This relationship is essential for understanding the reservoir's behaviour under different operational conditions, such as flood control, water supply, and hydropower generation. The stage capacity relationship of the Main Kandar Dam reservoir is shown in Figure 5a. The spillway crest level was measured at 363.72 m, while the lowest elevation, relative to mean sea level, was recorded at 357.05 m. The maximum storage capacity up to the crest level was determined to be 1,000,365 m³, representing the current storage capacity of the Kandar Dam.

Figure 5b represents the stage capacity relationship of the Auxiliary Kandar Dam. The spillway crest level was identified at 384.15 m. The lowest elevation, also indicating the maximum depth, was found to be 368.69 m above mean sea level. The maximum storage capacity up to the crest level was calculated to be 1,997,974.057 m³, which corresponds to the current storage capacity of the Auxiliary Kandar Dam.

Assessment of sediment trap efficiency using the capacity-to-inflow ratio

The capacity-to-inflow ratio was calculated using the designed live storage capacity of the reservoir and the observed long-term mean annual inflow. The live storage capacity was obtained from the approved design documents of the Irrigation Department of Khyber Pakhtunkhwa, while the average annual inflow was derived from the department's hydrological records. This ratio represents the residence time of sediment-laden water and thus informs the reservoir's sediment trap efficiency. A lower ratio indicates that most of the incoming sediment is flushed downstream during high-flow events, whereas a higher ratio implies longer retention, allowing more suspended sediment to settle within the reservoir.

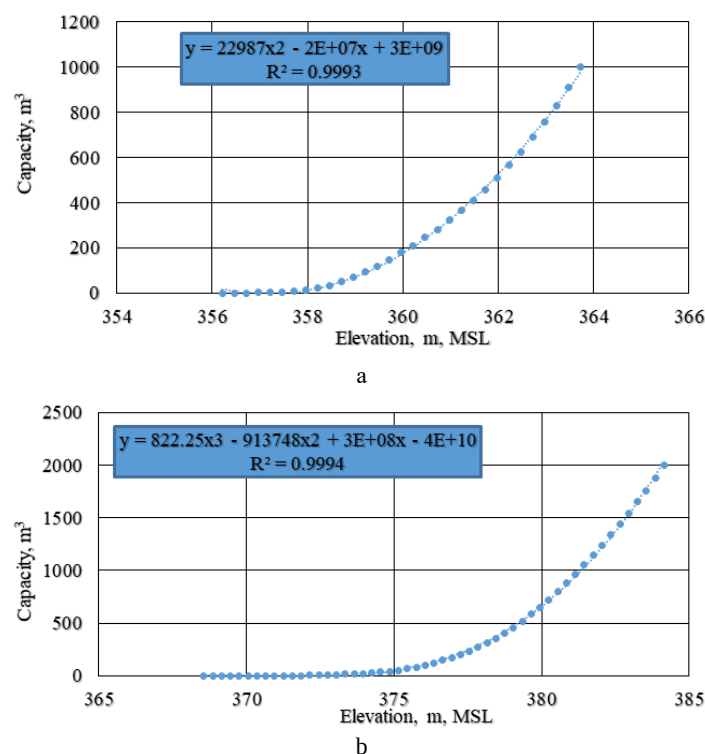


Figure 5. Stage capacity relationship of Main Kandar Dam and Auxiliary Kandar Dam: a – main dam; b – auxiliary dam

The relationship between reservoir capacity and annual inflow based on the guideline curve presented by Mao et al. (2016) is shown in Figure 6. This curve provides a practical basis for evaluating trap efficiency and is commonly applied in sediment management studies. According to HR Wallingford (2004), a capacity-to-inflow ratio of approximately 0.5 is recommended for catchments prone to severe degradation and elevated sediment yield. The average annual inflow of the Main Kandar Dam, as reported by the Irrigation Department of Khyber Pakhtunkhwa, was approximately 5,158,000 m³, which assists in determining its sediment retention behaviour.

Deposited sediment load and sedimentation rate of Main Kandar Dam reservoir

Sedimentation in dams or reservoirs stems from various natural and anthropogenic factors, collectively impacting the flow of water and the storage capacity of the reservoir. Natural erosion processes, primarily due to rainfall, runoff, and the natural movement of soil and debris, contribute significantly to sedimentation. Human activities exacerbate this phenomenon, with deforestation, agriculture, and construction leading to increased soil erosion and sediment runoff into water bodies. Urbanization further amplifies sedimentation through increased impervious surfaces and altered land use patterns. Poor land management practices, including improper soil conservation techniques and overgrazing, also accelerate sedimentation by

destabilizing soil and increasing erosion rates. Climate change-induced extreme weather events, such as intense rainfall and flooding, further exacerbate sedimentation by mobilizing large volumes of sediment into reservoirs. Addressing sedimentation requires a multifaceted approach, including sustainable land management practices, sediment trapping measures, and watershed management strategies aimed at reducing erosion and sediment transport into dams and reservoirs.

Table 1 presents calculations for sediment accumulation in the Main Kandar Dam which adversely affects the storage capacity of the dam. The storage capacity of Kandar Dam was measured at 11,758,866 m³ in 2016 by the irrigation department of Khyber Pakhtunkhwa. By 2022, this capacity had reduced to 10,003,365 m³, indicating a loss of 1,755,501 m³. This decline is attributed to sediment deposition within the reservoir over the preceding six years. The average annual sediment transport volume was calculated at 29,250.17 m³, with a sedimentation rate of 406.25 m³/km²/year, down from approximately 390 m³/km²/year in 2016.

The variation in sedimentation rate observed from 1972 to 2022 is shown in Figure 7. A clear decrease was noticed in the sedimentation rate during the proposed years. Although there was a slight increase in sedimentation rate during 2012, this may be attributed to extensive stone mining, intensive grazing in the catchment area, and a significant flood in 2010.

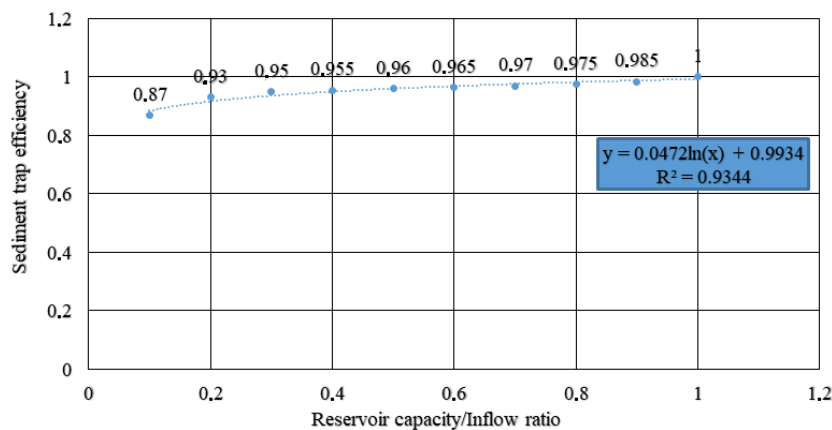


Figure 6. Sediment trap efficiency vs capacity-to-inflow ratio

Table 1. Sediment calculation for Main Kandar Dam reservoir

Year	Storage capacity, m ³	Loss in storage, m ³	Duration, years	Sediment transport, m ³ /year	Catchment area, km ²	Sediment rate, m ³ /km ² / year
2016	1,175,866	–	–	–	72	–
2022	1,000,365	175,501	6	29,250.17	72	406.25

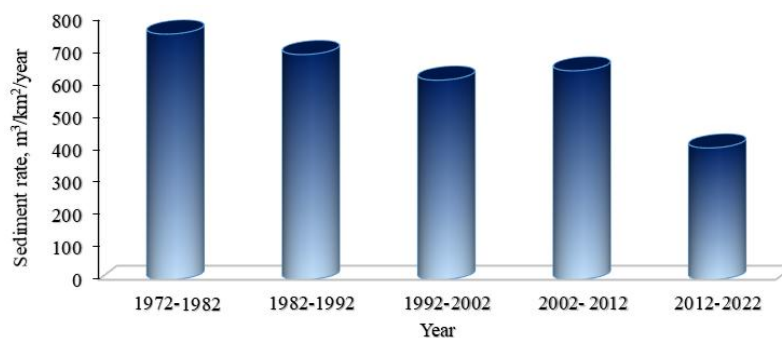


Figure 7. Sedimentation rates of Main Kandar Dam reservoir from 1972 to 2022

Deposited sediment load of Auxiliary Kandar Dam reservoir

The Irrigation Department of Khyber Pakhtunkhwa determined the design storage capacity of Auxiliary Kandar Dam to be 2,194,628 m³ in 2013. However, subsequent assessments in

2022 revealed a decrease in storage capacity to 1,997,974 m³, indicating a loss of 196,654.15 m³, as shown in Table 2. This decline in capacity is primarily attributed to sedimentation within the reservoir over the past nine years. The average annual sediment transport volume was measured at 21,850.46 m³, with a sedimentation rate of 458.75 m³/km²/year.

Table 2. Sediment calculation for Auxiliary Kandar Dam reservoir

Year	Storage capacity, m ³	Loss in storage, m ³	Duration, years	Sediment transport, m ³ /year	Catchment area, km ²	Sediment rate, m ³ /km ² / year
2013	2,194,628	–	–	–	47.63	–
2022	1,997,974	196,654	9	21,850.44	47.63	458.74

Estimation and comparison of sediment yield through the Wallingford model

The catchment areas of the Main Kandar Dam and the Auxiliary Kandar Dam were designated by the Irrigation Department of District Kohat, Khyber Pakhtunkhwa. According to data from the Pakistan Meteorological Department (PMD), the average rainfall in the catchment area was 568 mm. The Vegetation Cover (VC) scored an average of 40, indicating that approximately 80% of the catchment area had bare ground, sparse cover, or limited effective plant cover. The score for Soil Type and Drainage (STD) and Signs of Active Soil Erosion (SASE) was 20. This was due to the presence of moderately well-drained, medium-textured soil in the catchment area, with some instances of ponding on the soil surface observed after heavy rainfall during the survey. Additionally, actively eroding gullies were discovered draining directly into the reservoirs of both dams and moderate undercutting of river banks along the main waterways was observed during the catchment area survey.

A comparison of sediment yield estimated using the Wallingford model with observed data is shown in Figure 8. Sediment rates determined by the Wallingford model were 357.02 m³/km²/year and 387.38 m³/km²/year for Main Kandar Dam and Auxiliary Kandar Dam, respectively. Conversely, sediment rates estimated through grid survey were 406.25 m³/km²/year and 458.75 m³/km²/year for Kandar Dam and Auxiliary Kandar Dam. These figures contrast with the recorded rate of 390 m³/km²/year in 2016. The predictions of the Wallingford model are lower than observed sediment rates, potentially due to climatic conditions, overgrazing, and agricultural practices in the watershed. These factors accelerate soil erosion and sedimentation, which were not accounted for in the Wallingford model.

Temporal variations in the storage capacity of the reservoir

The designed storage capacity of the Kandar Dam in 1972 was 2,618,000 m³, as shown in Figure 9. By the year 2022, the reservoir's capacity had decreased by 61.78% compared to the original estimation in 1972. With the construction of the Auxiliary Kandar Dam in 2014, sediment deposition in the

Main Kandar Dam decreased by 7% for six years (2016 – 2022).

Capacity-inflow ratio and sediment trap efficiency

The capacity inflow ratio and sediment trap efficiency of the Main Kandar Dam were determined for the duration from the initial construction in 1972 to 2022, which included different monitoring stages with their corresponding sediment trap efficiencies in between them. In response to the capacity inflow ratio of the Main Kandar Dam reservoir of 0.194, the trap efficiency reached 90.48% in 2022. The trap efficiency of the Main Kandar Dam reservoir has decreased with the decrease in the capacity inflow ratio from 0.508 to 0.194.

Annual sediment rates of Main Kandar Dam reservoir

The annual sediment rates of the Main Kandar Dam reservoir were 49733 m³/year in 1972 – 1982 and 54251 m³/year in 1982 – 1992. In contrast, the annual rates estimated during 2002 – 2012 and 2012 – 2022 were 27945 m³/year and 29250 m³/year, respectively, as depicted in Figure 10. The sediment rates observed from 1972 – 1982 and 1982 – 1992 were significantly higher compared to those estimated in 2002 – 2012 and 2012 – 2022, indicating a decrease in annual sediment rates. This decline could be attributed to the construction of the Auxiliary Kandar Dam upstream.

Life of Kandar Dam before and after the construction of the auxiliary dam

The effective lifespan of the Main Kandar Dam reservoir was determined to be 34 years based on the observed total capacity loss. A comparison of the effective lifespan of the Main Kandar Dam reservoir under various scenarios (pre- and post-construction of the Auxiliary Kandar Dam) was conducted using observed rates from 1992 and 2022. Detailed summary calculations of this comparison are presented in Table 3. In 2016, the reservoir's capacity was calculated to be 1,175,865 m³ using the reverse calculation from the 2022 rate, with an observed effective lifespan of 14 years according to the Irrigation Department. The construction of the Auxiliary Kandar Dam was found to extend the effective lifespan of the Main Kandar Dam reservoir by 26 years.

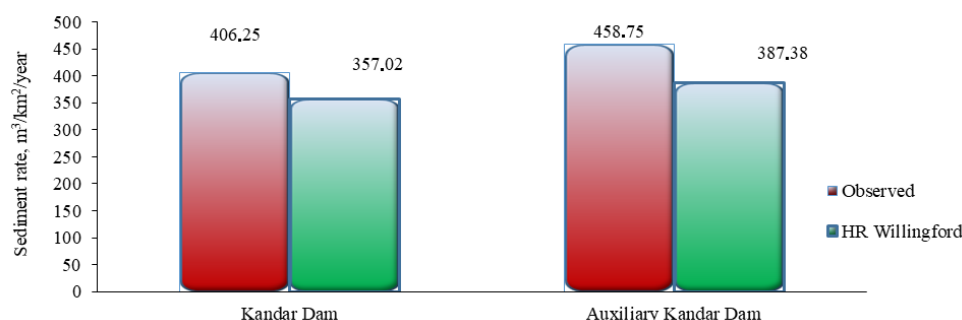


Figure 8. Comparison of sediment rates

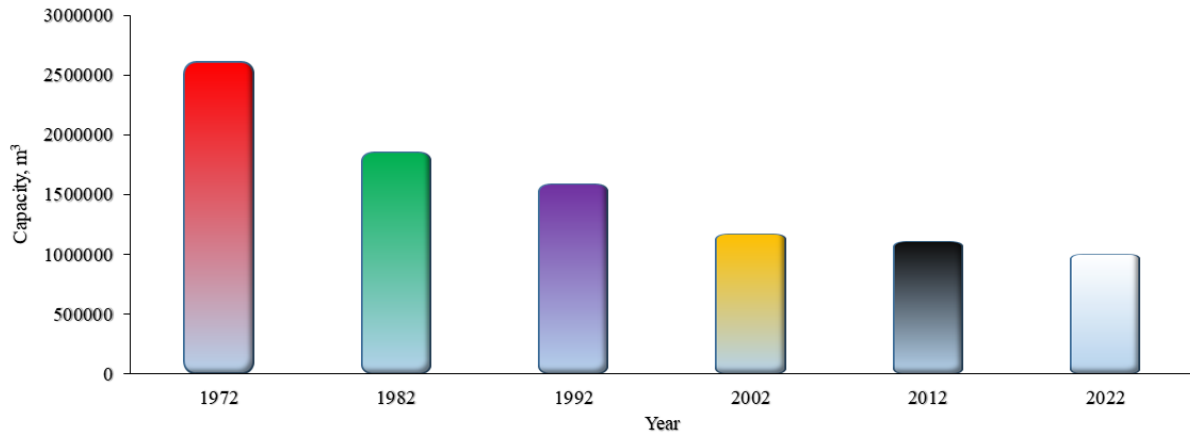


Figure 9. Temporal variations in the storage capacity of Main Kandar Dam reservoir

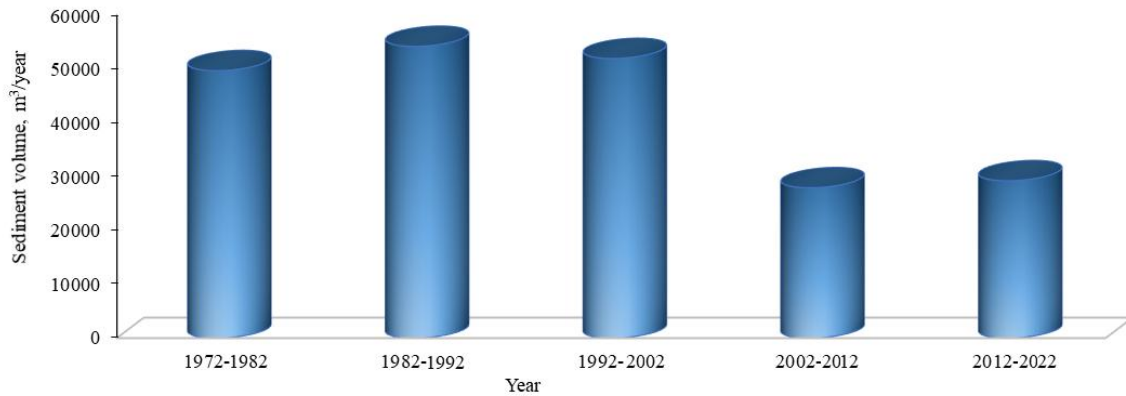


Figure 10. Annual sediment rates of Main Kandar Dam Reservoir from 1972 to 2022

Table 3. Effective lifespan of Kandar Dam before and after the construction of the auxiliary dam

Scenarios	Year of assessment	Sediment rate, m³/year	Reservoir capacity, m³	Effective life, year		Increase in lifespan, year
		1992 (54,251 m³/year)	2022 (29,250 m³/year)	1992	2022	
Before construction	2013	941,441	1,263,615	17	43	26
After construction	2016	778,688	1,175,865	14	40	26
Observed (post construction)	2022	453,182	1,000,365	8	34	26

Projected outcomes from different scenarios

There are different possible ways due to some additional values that have been incorporated or in the future to be incorporated into the existing infrastructure. These are as follows.

Construction of the Auxiliary Kandar Dam in 2002

If the Auxiliary Kandar Dam, which was built in 2014, had been constructed in 2002, the lifespan of the Main Kandar Dam could have been extended by 44 years (from 2022 to 2066) instead of the current 34 years, assuming the present rate of 29,250 m³/year. Consequently, the Main Kandar Dam's lifespan might have extended to 2066 instead of its current projected end in 2056.

Construction of the new proposed Auxiliary Kandar Dam on the left waterway

The construction of the existing auxiliary dam on the right waterway in 2014 has prolonged the lifespan of the Main Kandar Dam by 34 years. If both the existing auxiliary dam on the right waterway and the proposed new auxiliary dam on the left waterway had been built simultaneously in 2002, the lifespan of the Main Kandar Dam might have been extended by 90 years from the existing auxiliary dam in the 2002 scenario, and by 134 years from the present situation (2022 to 2156).

Doubling the Auxiliary Kandar Dam Simultaneously in 2014

If two auxiliary dams had been constructed simultaneously at both waterways, the lifespan of the Main Kandar Dam would have been extended by 52 years (from 2056 to 2108) and 86 years (from 2022 to 2108) compared to the current situation.

Addition of an Auxiliary Kandar Dam in 2016 or 2022 on the left waterway

The right auxiliary dam was built in 2014. If the left bank auxiliary dam had been constructed in 2016, the lifespan of the Main Kandar Dam could have been extended by 80 years (2022 – 2102). If the same dam had been constructed in 2022, the lifespan of the Main Kandar Dam might have increased by an additional 68 years (2022 – 2090) compared to its actual construction.

Addition of another Auxiliary Kandar Dam in 2025

If the proposed left auxiliary dam is constructed in 2025, it is anticipated that the lifespan of the Main Kandar Dam will be extended by 66 years, lasting from 2022 to 2088. This option is the sole alternative perceived to potentially elongate the Main Kandar Dam's lifespan by an additional 65 years, projecting its longevity from 1972 to 2079, totalling 107 years.

DISCUSSION

Dams play a crucial role in water management and energy production worldwide. The construction of dams, however, can have significant impacts on the riverine material cycle and ecology (Wang et al., 2018). One of the major concerns associated with dam construction is sedimentation. Sedimentation refers to the accumulation of sediments, such as soil, sand, and rocks, in reservoirs behind dams. Sedimentation can have negative consequences for both the environment and the functionality of the dams themselves. It can lead to a reduction in storage capacity, increased flood risk downstream, and altered water quality. The study is an attempt to determine sedimentation rates in small dams by estimating annual sediment loads in the reservoirs of Kandar Dam and Auxiliary Kandar Dam, comparing sediment yield estimated by HR Wallingford model, with observed rates, and evaluating the effective lifespan before and after the construction of the Auxiliary Kandar Dam upstream.

The storage capacity of the Auxiliary Kandar Dam plays a crucial role in water management and provides irrigation opportunities for the surrounding areas (Anzai et al., 2017). The complex network of channels in the drainage system, along with the flat topography of the area, creates natural basins that function as rainwater catchment reservoirs. These reservoirs serve as a means of storing water during dry periods, allowing for the retention of a substantial proportion of precipitation falling on the basin. However, it is important to consider the antecedent conditions that can affect the storage capacity of the basin (Macrae et al., 2010). These conditions include the hydraulic conductivity of soils and the elevation of the water table (Bukovskiy et al., 2020). During dry periods, when the storage capacity of the basin is high, a greater amount of precipitation is expected to be retained. On the other hand, during wetter conditions, the storage capacity of the basin is reduced and there is an increase in runoff through upper soil horizons due to the elevated water table and increased hydraulic conductivity of soils.

Recent research studies concerning the deposited sediment load within the Main Kandar Dam reservoir have shed light on key aspects of reservoir management and sustainability. Studies conducted by Mamede et al. (2018) and Amasi et al. (2021)

have emphasized the importance of understanding sediment dynamics in reservoirs to mitigate the impacts of sedimentation on water storage capacity and downstream ecosystems. Their findings indicate a significant increase in sediment deposition rates compared to historical data, suggesting a potential acceleration in sedimentation processes. Xoshimov et al. (2022) further investigated the sources and composition of sediment in the reservoir, employing sediment fingerprinting techniques and sediment transport modelling. Their research revealed that anthropogenic activities such as deforestation and land use changes in the watershed have substantially contributed to sediment influx into the reservoir, exacerbating sedimentation rates. The implications of these findings underscore the urgent need for proactive sediment management strategies, including sediment dredging, watershed conservation measures, and sustainable land use practices, to maintain the long-term functionality and ecological integrity of the reservoir.

The results of the study also highlight the utilization of the Wallingford Model to predict sediment yield in various geographical contexts, ranging from small catchments to large river basins. For example, a study by Dalu et al. (2013) applied the Wallingford Model to estimate sediment yield in the Malilangwe reservoir in the south-eastern lowveld of Zimbabwe, highlighting its effectiveness in predicting sediment transport dynamics over different spatial and temporal scales. Similarly, Worrall et al. (2014) employed the Wallingford Model to assess sediment yield in mountainous regions of the United Kingdom, demonstrating its utility in areas with complex terrain and varying erosion processes. Despite its widespread application, some researchers have raised concerns about the accuracy of the Wallingford Model under certain conditions, such as in highly disturbed or anthropogenically influenced watersheds.

Sedimentation-related problems

Sedimentation encompasses erosion, transportation, deposition, and compaction of sediments (Chabalala et al., 2017). It occurs in reservoirs when sediments carried by river flow settle into the reservoir. Various researchers have documented both direct and indirect adverse effects of reservoir sedimentation upstream, downstream, and at the dam site (Annandale et al., 2016; Huang et al., 2019; Kong et al., 2020; Ren et al., 2021; Sedláček et al., 2022). Notably, multiple studies have investigated and reported on these consequences, providing valuable insights into the impacts of sedimentation.

De Araújo et al. (2006) conducted a case study to evaluate the impact of reservoir sedimentation on water availability in semi-arid regions, finding that the risk of water shortage nearly doubled in less than 50 years. Similarly, Kummu & Varis (2007) examined the effects of sedimentation on the hydrology, sediment flux, and geomorphology of a hydropower dam in the Lower Mekong Basin in China, revealing a reduction of more than half in the annual sediment flux at a distance of 660 km downstream from the dam. Fu et al. (2008) observed significant downstream impacts due to high sedimentation rates in the Manwan Reservoir in China. Wildi (2010) reviewed various potential hazards associated with dam and reservoir operations. Chen et al. (2012) investigated the morphological changes induced by the construction of the Xiaolangdi Dam on the lower Yellow River during its initial 10 years of operation, noting a substantial upstream river elevation increase (up to 10 m), reduction in river widths (up to 50%), flow area (up to 50%), and decreased flood transporting capacities by 42 – 61%, leading to increased flood disasters in North China. They also reported significant erosion downstream of the dam,

particularly in the upper reach of the river (upper 35% of the river's length), along with armouring of downstream riverbed material, resulting in bed materials approximately twice as large by 2009 compared to 1999. Additionally, Xie et al. (2015) investigated the impact of the Three Gorges Dam on the downstream eco-hydrological characteristics and vegetation cover of East Dongting Lake, China, finding rapid increases in both vegetation cover rates and the lowering of the minimum elevation of the vegetation-covered area following dam construction.

CONCLUSION

This study aimed to assess the impact of the Auxiliary Kandar Dam on the lifespan of the Main Kandar Dam and to evaluate sedimentation patterns in the catchment area. The goal was successfully achieved, as the analysis demonstrated that sedimentation has significantly reduced the storage capacities of both dams, by approximately 61.78% over 31 years for the Main Kandar Dam and 9% over 9 years for the Auxiliary Kandar Dam. Importantly, observed sedimentation rates deviated from predictions by the HR Wallingford model, highlighting the limitations of existing models in accurately forecasting local sediment dynamics.

A key new finding of this study is the quantification of the Auxiliary Kandar Dam's contribution to extending the effective lifespan of the Main Dam by 34 years (2022 – 2056). Moreover, scenario analyses revealed that additional proposed auxiliary dams could potentially extend the lifespan of the main dam by up to 134 years (2022 – 2156). These findings fill a critical knowledge gap regarding the effectiveness of auxiliary structures in sediment management and reservoir lifespan extension, a topic that has not been fully addressed in prior studies of the region.

The study also provides actionable prospects for water resource management in the study area. Constructing a second auxiliary dam on the left waterway in 2025 could extend the lifespan of the Main Dam to 2089, offering an additional 64 years of service (2025 – 2089). Furthermore, the development of irrigation systems from both auxiliary dams presents opportunities to expand the watershed's command area, enhancing agricultural productivity and regional water security.

Overall, this study not only confirms the value of auxiliary dam structures in prolonging reservoir life but also provides a scientific basis for future planning, offering strategies to

mitigate sedimentation impacts and optimize water resource management in similar semi-arid regions.

Author's statements

Contributions

Conceptualization: A.S., F.A.; Data curation: D.B.; Formal Analysis: F.A.; Investigation: B.A.; Methodology: B.A., R.S.; Software: D.B., F.A.; Supervision: F.A., D.B.; Validation: G.D.K.; Visualization: A.S., G.D.K.; Writing – original draft: A.S., S.N.; Writing – review & editing: F.A.

Equal contribution by Shahab Noor and Awais Salman.

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The authors declare no competing interests.

Financial interests

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Data availability statement

All authors of this manuscript confirmed that the data supporting the findings of this study are available within the manuscript, and all the required data are available and easily accessible.

AI Disclosure

The authors declare that generative AI was not used to assist in writing this manuscript.

Ethical approval declarations

All applicable international, national, and institutional guidelines for the care of both human and animal studies were followed in this research work.

Additional information

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