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Evaluation of sediment generation and transport: a case study of Thwake Dam in Kenya

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ABSTRACT

The study aimed to evaluate sediment generation, transport, and deposition into the Thwake reservoir. This research sought to assess sediment transport patterns and their potential impact on the reservoir using regional and numerical techniques. The Thwake River basin constitutes 30% of the dam's catchment area and experiences high soil-loss due to its semi-arid climate, steep slopes, and lack of vegetation. The river system in the sub-basin is ephemeral, with the riverbed remaining dry throughout most of the year and experiencing tidal flow only during storm events. Bed-material samples were collected from selected reaches, and sediment properties were evaluated. The study involved analyzing datasets on the reservoir, catchment, and sand-bed channel. Numerical models assessed hydrological and sediment transport information by considering interacting variables and predicting deposition patterns and sediment-yield estimates. The findings indicated that sufficient bed material from sub-basin 3E would be deposited into the reservoir, resulting in delta formation approximately 5 km downstream of the tail waters at minimum dam operating level. The mass cumulative sediment inflow from 3E into the reservoir was estimated as between 14 and 26.3 metric tons per annum, representing reservoir loss and useful life under 50 years.

Key words: climate change, sand dams, sediment generation, transport

HIGHLIGHTS

- Effective water resource management in reservoirs and rivers, ensure infrastructure longevity.
- Design of resilient infrastructure minimizing sediment-related risks and enhancing performance.
- Considers climate-change adaptation giving real-time monitoring.
- Research aids in quantifying sources and implementing erosion-control measures and restoration efforts.
- Value engineering for cost-effectiveness in extending a reservoir's useful life.

1. INTRODUCTION

The problem of sediment deposition and accumulation in reservoirs without a management strategy poses challenges to the long-term benefits accrued from water conservation. In managing scarce water resources, constructing multi-purpose dams ensures regulated and reliable water allocation and efficient use through harvesting and conservation. From a global context, the sediment problem limits the guaranteed sustainable use of reservoirs worldwide due to storage loss. Studies indicate that loss of storage capacity is higher than increased capacity by the construction of new dams.

The Sennar Dam was constructed across the Blue Nile in 1925; a study showed that the sedimentation rate in the reservoir in the period 1925–1981 was 0.5% per year, meaning a 28% reduction in reservoir capacity occurred in the 56 years of operation. Between 1981 and 1986, sedimentation rates increased to 5.8% due to changes in operation rules to satisfy hydropower requirements and irrigation, resulting in a 29% loss in storage in just five years (Gismalla *et al.* 2015). The loss in storage impacts the dam flood-attenuation capabilities and results in reduced benefits in the long run and eventual decommissioning.

Adjacent catchment data of the Tana Basin in Kenya all estimate sedimentation rates between 350 and 1,000 t/km^2/year. High-yielding sediment basins with estimated values over 19,520 t/km^2/year were recorded in the Perkerra River basin in Baringo, Kenya (Garde & Ranga Raju 2000). A detailed report for Thwake Dam (SMEC 2018) gave an estimated sedimentation of 569,964 m^3/km^2/year, which translates to 55–80 t/km^2/year. Maruba Dam in the Thwake River basin, constructed in 1950 (Phase 1), had an estimated sediment yield of 650 m^3/km^2/year from the bathymetric survey conducted in 2008

(NWCPC_NWHSA 2008) and subsequently another study reported an estimated yield of 517 m^3/km^2/year (Luvai *et al.* 2022).

Analysis of sediment transport formulas using common equations like Ackers–White, Bagnold, Yang, Colby, Shen and Hung, and Engelund–Hansen were assessed in estimating sediment yield using Euphrates River data from Al Anbar province, Iraq (Sulaiman *et al.* 2021). The Engelund–Hansen formula showed superior accuracy in predicting sediment loads. The research aimed at enhancing understanding of Euphrates River sediment dynamics, supporting informed decisions on river-bank management and infrastructure development. Annual sediment loads in the Euphrates River within Al Anbar province have ranged from 1.9×10^6 to 2.1×10^7 t/year (Al-Ansari *et al.* 2015). Therefore, the sediment transport equation will be applicable to specific reach conditions and sediment properties. Similarly, cesium-137 was used as a tracer in soil erosion studies due to its widespread distribution in soil and was used as a case study to assess deforestation and its impact on soil erosion (Gharibreza *et al.* 2020). A radioactive isotope of cesium is a chemical element with the atomic number 55 (Snow & Snyder 2016). It is formed as a byproduct of nuclear fission processes, commonly found in nuclear waste and fallout from nuclear-weapons testing. ^{137}Cs emits gamma radiation, making it useful in various applications such as radiological dating and environmental monitoring. By measuring its concentration at different depths within soil profiles, erosion rates can be estimated over time. This involves drying soil samples, grinding and homogenizing, before sieving to separate finer portions, and ^{137}Cs activity is then measured by extracting it from soil-core samples and measuring it using gamma spectrometry. Such analysis provides data on soil redistribution dynamics and erosion patterns applicable in areas already exposed to the isotope.

Thwake River exhibits a consistent trend where bed-load transport increases with rising flow and contributions made by ephemeral streams in the transport of bed-load material have indicated the smallest stream power (ω*) value observed in the ephemeral stream is approximately 2.5 times larger than the largest value recorded in the perennial stream (Almedeij & Diplas 2005). In addition, unique bed-load stratification patterns are formed compared with the perennial Athi River, suggesting a continuum in bed-load transport rates with increasing stream power (Almedeij & Diplas 2005). Ephemeral streams demonstrate higher bed-load transport efficiency under similar flow conditions. By applying theories developed for perennial streams, bed-load transport rates in ephemeral gravel streams are simulated, offering practical insights for reservoir management and channel stability assessment.

To estimate sediment transport effectively, a comprehensive approach combining field measurements, empirical relationships, and numerical modeling is employed. During the study, field survey data were gathered, including climate data, hydraulics, sediment samples, and channel characteristics. Empirical equations were used to estimate sediment transport rates. Numerical models to simulate flow, sediment transport, and morphological changes were observed. Calibration and validation ensured accuracy using existing inline structures, while scenario analysis predicted the impacts of deposition over time and the storage life of Thwake Dam.

This study utilizes spatial geographical data and quantitative climate data to develop the numerical model using one-dimensional movable-boundary open-channel flow and sediment simulations using a combination of GIS, HEC-HMS, and HEC-6 RAS Mapper. This integrated method offers valuable insights into sediment dynamics, erosion processes, and sedimentation patterns, guiding river management strategies efficiently. The model output evaluates the impact of sediment generation and transport within the river basin and within the reservoir. The study outcome contributes to sediment management strategy for reservoir conservation and enabling the best decisions on optimum economic operation for maximum benefit.

2. MATERIALS AND METHODS

2.1. Study site

The study area covers sub-basin 3E, Thwake sub-basin in the larger Athi Basin in Kenya. Thwake Dam is constructed across the Galana River and is located 120 km south-east of the capital Nairobi. The dam operation prioritizes environmental release and allocation to domestic, industrial, irrigation, and hydropower-generation uses. The point of interest is located at WGS 1984 UTM Zone 37 M, 3,370,848.02 m E, 9,802,190.41 m S. Figure 1 shows the project area, sub-basin, river system, and dam location.

2.2. Data collection

The initial part of the study involved data collection and desk study to establish hydromet monitoring information, sediment sampling, and analysis. The Landsat data was used for land classification and processed using GIS, online sources from

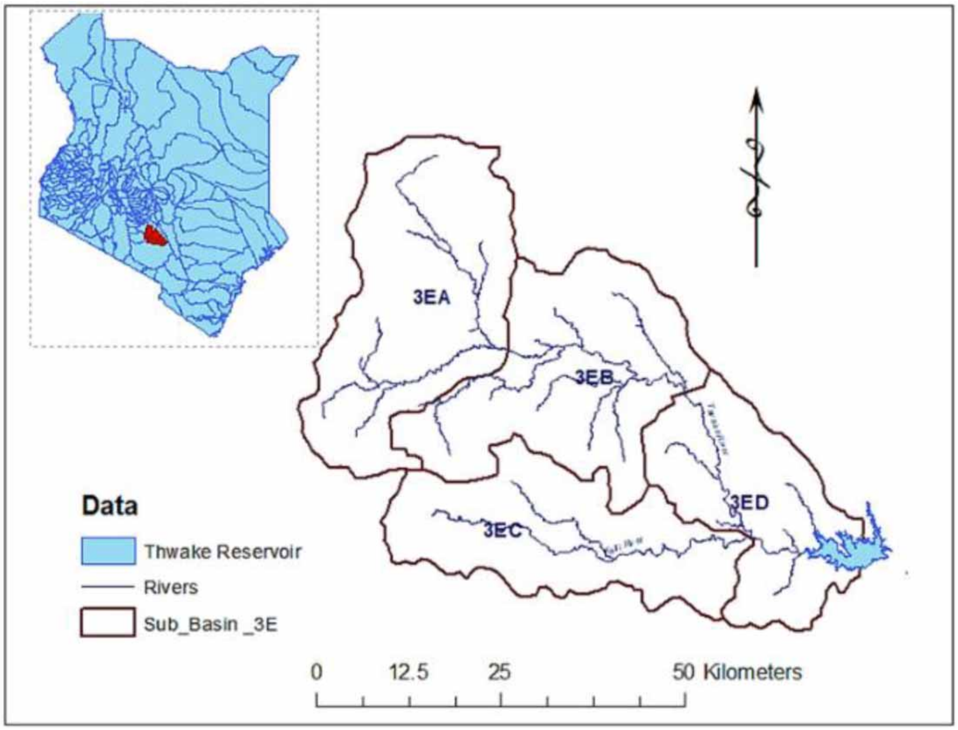

Figure 1 | Study area.

Group on Earth Observations (GEO) and Google Earth Engine (GEE). Hydraulic modeling for sediment transport was developed based on geometric data, flow data, sediment data, and sediment analysis. The model estimates sediment transport potential across selected reaches along the Thwake River basin and upstream of the reservoir from raw data collected, stored, and interpreted.

Climate impact was considered based on climate data from IPCC AR5 SimCLIM and CODEX models (ISC 2020), and UK Met Climate Change models for East Africa 2022. The rainfall datasets comprised hydromet stations identified within the sub-basin with reliable data, which were stations 9137003, Malili Ranch; 9137003, Machakos Agro Met Station; and 9137003, Ngelani Youth. Records from the years 1961, 1962, 1997, and 1998 were used due to extreme recorded storm and available data. Penman–Monteith (PM) reference evapotranspiration (ET_0) values were calculated using the ET_0 calculator developed by the FAO. The calculator uses the minimum and maximum temperatures, mean relative humidity, mean wind speed, hours of bright sunshine, and solar radiation sourced from the CLIMWAT for CROPWAT 2.0 database to calculate the average monthly ET_0 in millimetres per day (FAO 2022b).

A digital soil map was obtained in a vector dataset based on the FAO-UNESCO soil map of the world (FAO 2022a). The digitized soil map is at 1:5,000,000 scale, and geographic projection (latitude–longitude) intersects with a template containing water-related features. The dominant soil groups identified are BC (Black Cotton; 40% sand, 21.5% silt, 38.4% clay, and 1.44% organic matter), FR (Ferralsol; 40.4% sand, 14.8% silt, 44.6% clay, and 1.52% organic matter), LF (Luvic Ferralsol; 74.6% sand, 9.6% silt, 15.9% clay, and 0.39% organic matter), and VP (Vertisol; 25.1% sand, 12.2% silt, 62.7% clay, and 0.68% organic matter). Catchment, riverbank, and bed-load samples were collected and organic content and grading sampling were carried out. The four dominant soil-groups are shown. The bed-load material results indicated that it constitutes mainly coarse to medium sand (0.05–2 mm). Figure 2 illustrates the soil coverage in the project area and Lidar data from the project area.

2.3. Data analysis

The river morphology is examined, specifically the banks, slopes, and sinusoids. Studies on the land-cover data during wet and dry seasons were evaluated using land-cover data obtained from Landsat 4–5 Thematic Mapper (TM).

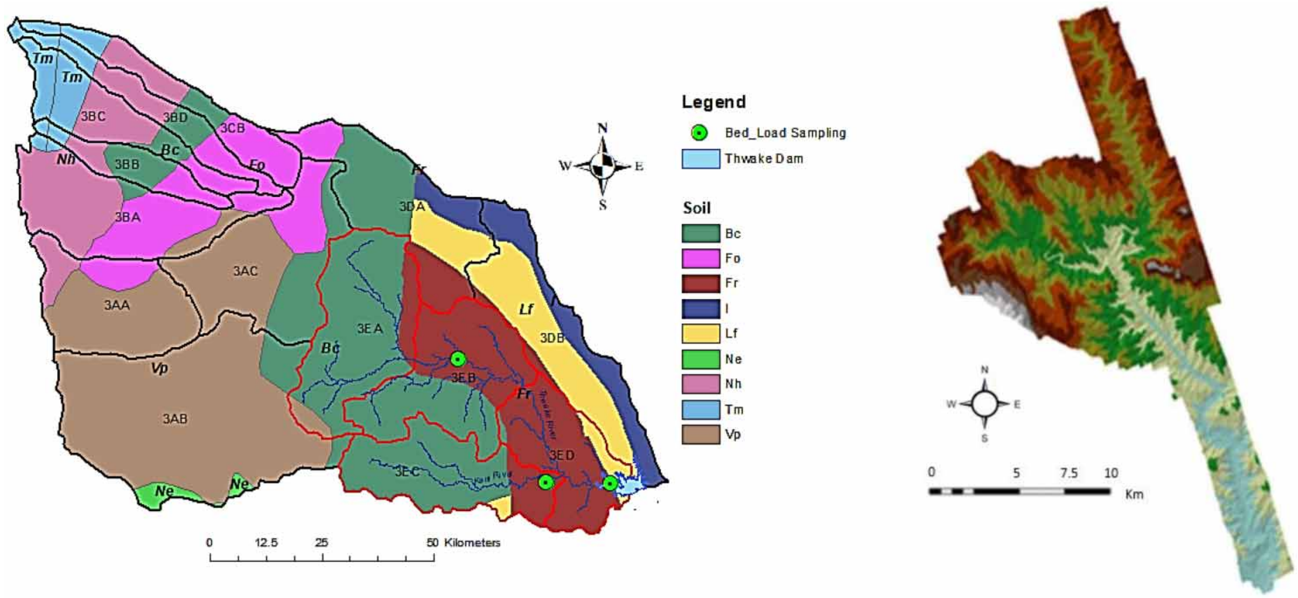

Figure 2 | Thwake Dam spatial soil-distribution and Lidar data.

An event-based model was developed for an extended period to simulate different sediment output values using data on concentrations and flow regimes, among other conditions and controls. The research evaluated sensitivity checks on climate-change parameters and observed impacts on the reservoir. Longitudinal deposition of sediment into the reservoir is a phenomenon referred to as delta deposit.

The primary impact of these delta accumulations is the elevation increase in backwater levels within the channel upstream of a reservoir. Consequently, the delta formation can introduce flood risks that may not have been foreseen during the design phase. Sediments deposited in the delta undergo continuous reworking into the downstream storage region, particularly during periods of low-reservoir stage and extreme flood discharges. The delta forms based on particle sizes and deposits in the extreme upstream portion of the profile. Although the delta study is used in defining additional inundated areas caused by backwater, it is critical in managing an advancing delta in the reservoir safe storage areas as explained in subsequent sections.

Three different methods may be used to compute the concentration of sediment in water; concentration by mass was adopted in this study. C_m refers to the sediment mass per unit volume of the water–sediment mixture and, by definition, $C_m =$ sediment mass/volume of mixture. The river reaches were routed using the Muskingum routing method by applying the conservation-of-mass approach using finite differential equations to route flow through the stream reach. The continuity equation is $I - Q = dS/dt$, where I is inflow, Q is outflow, and dS/dt is change of storage with time, and storage is given by:

$$S = K\{XI + (1-X)Q\} \tag{1}$$

where K is the estimated travel-time through the reach based on the cross-section obtained from the digital elevation model and flow properties from simulations. The Muskingum X (inflow and outflow influence) was calibrated between 0.25 and 0.35 in the sub-reaches.

The computation of initial sedimentation and establishment of the top set slope is computed using the mathematical zero bed-load transport slope from the bed-load equations by Meyer-Peter (Strand & Pemberton 1982). The equation by Meyer-Peter and Müller adopted for zero bed-load transport is given by:

$$S = K \frac{\frac{Q}{Q_B}\left(\frac{n_s}{n_{90}^{1/6}}\right)^{3/2}}{d} \; D \tag{2}$$

where S is the delta top set slope, K is a coefficient equal to 0.058, Q is total flow (m^3/s), Q_B is flow over the bed of the stream (m^3/s), D is the mean diameter of sediment, and d is the depth of the pool. The sediment erosion and transport were iteratively calibrated against suspended measured sediment loads.

Sediment discharge and prediction of deposition into the Thwake reservoir were computed using HEC-6, a one-dimensional movable-boundary open-channel flow model that computes sediment scour and deposition by simulating the interaction between the hydraulics of the flow and the rate of sediment transport. The model incorporates the assumption that equilibrium conditions are achieved between the flow and the bed-material transport within each time-step, an assumption also made in most other sediment transport models (Morris & Fan 1998). This assumption may be violated during rapidly rising and falling hydrographs, which can limit the model's ability to simulate single events. For this reason, the HEC-6 program documentation specifically states that the model is designed for the analysis of long-term river and reservoir behavior. However, in practice, it has also been used to simulate single events (HEC 2022).

The number of scenarios using an upper limit 'accelerated' sedimentation yield value obtained from the Revised Universal Soil Loss Equation (RUSLE) is given by the following equation:

$$A = R \times K \times LS \times C \times P \tag{3}$$

where A is the average annual soil loss (in t/acre/year), R is the rainfall–runoff erosivity factor (measures the erosive force of rainfall), K is the soil erodibility factor (represents the susceptibility of soil to erosion), LS is the slope length and steepness factor (accounts for the combined effect of slope length and steepness on erosion), C is the cover and management factor (evaluates the protective cover provided by vegetation and land management practices), and P is the support practices factor (assesses the effectiveness of erosion control practices such as terracing or contour farming).

Transport functions were defined based on site-specific data and empirical relationship. The choice of transport function depended on the type of sediment being modeled (e.g., sand, gravel, silt). The Ackers–White formula was adopted, which is suitable for estimating sediment transport rates in sand-bed rivers and channels. It incorporates empirical coefficients to account for the effects of flow velocity and sediment characteristics.

$$V = n/k \times R^{2/3} S^{1/2} \tag{4}$$

where V is the mean velocity of flow (m/s), k is a dimensionless coefficient dependent on channel shape and roughness, n is Manning's roughness coefficient (dimensionless), R is the hydraulic radius (m), defined as the cross-sectional area divided by the wetted perimeter, and S is the slope of the channel bed (m/m).

The fall velocity was computed using the Rube equation for various diameter ranges:

$$\omega = \frac{(s-1)dy}{18v}, \quad 0.001 < d < 0.1\,\text{mm}$$
$$\omega = \frac{10^v}{d}\left[\left(1 + \frac{0.01(s-1)gd}{v^2}\right)^{0.5} - 1\right], \quad 0.1 < d < 1\,\text{mm}$$
$$\omega = 1.1[(s-1)gd]^{0.5}, \quad d \geq 1\,\text{mm} \tag{5}$$

where ω is the fall velocity, s is the slope, d is the particle diameter, and v is the velocity.

3. RESULTS AND DISCUSSION

3.1. Sediment discharge

The various sediment concentrations were generated based on sediment yield values and sampled data, and the graphical data obtained is shown in Figure 3. The sediment concentration values were based on flow profiles simulated using results from the HEC-HMS model for extended periods with data from the El Niño events of 1961–62 and 1997–98.

Figure 4 is sediment discharge based on various concentrations, plotted using the rainfall data in the basin, and flow relationships were also established using HMS and water-level gauge readings after the confluence of the Thwake and Athi rivers [3F02].

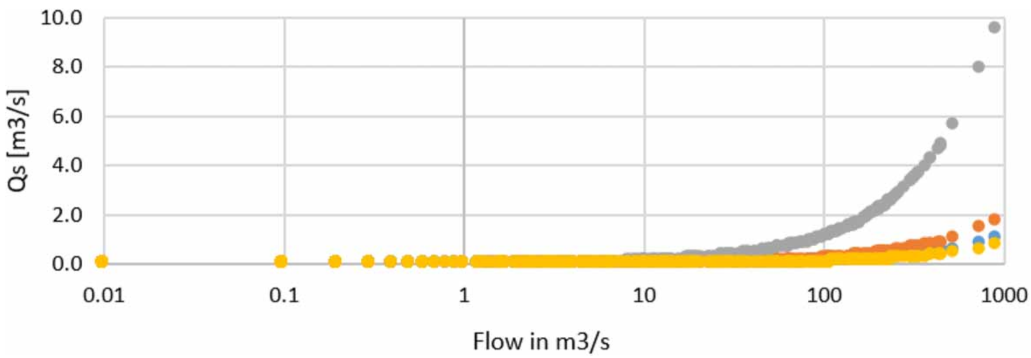

Figure 3 | Estimated sediment concentration values.

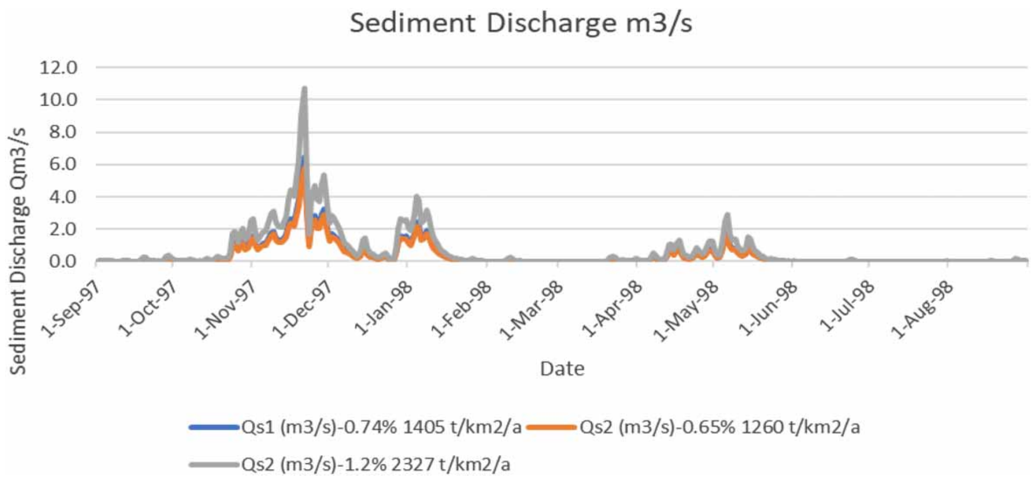

Figure 4 | Estimated sediment discharge values.

Sediment erosion and transport were iteratively calibrated against the HMS runoff values with different sediment concentration values. Since there is no regular gauging station in sub-basin 3E, correlation between RGS 3F02 (1 km downstream of confluence) and RGS 3DA02 (upstream of confluence) was plotted and a mass balance developed with discharge from 3E.

Figure 5 shows water-flow from different sub-basins, plotted using the rainfall data in the basin and flow relationships were also established using HMS and water-level gauge readings after the confluence of the Thwake and Athi rivers [3F02]. Flow correlations between 3F02 and 3DA02 were established, with $R^2 = 0.959$. The estimated flow contribution from 3E was between 200M and 300 MCM/a, and these values compare well with the findings from JICA (2013) of approximately 198 MCM contributing approximately 20%–25% annual flow to Athi River. For the sediment concentration values, the simulation was calibrated within the upper and lower bounds on the sediment concentration curves based on values of the RUSLE and bathymetry survey.

The bathymetric survey information was relied based on data from Maruba Dam located within sub-catchment 3E and Masinga Dam in the adjacent catchment. Applying the climate factor to the model was compared with estimated sediment yield results from dams in semi-arid areas in USA sediment (Brandt *et al.* 2017). The soil moisture accounting (SMA) loss method included in HEC-HMS was employed to model infiltration losses combined with canopy and surface methods.

Figure 6 illustrates flow simulation using hydrological modeling from rainfall–runoff in HMS.

The process of sediment gradation was based on ASTM-C 33 2003, the sediment limits were set from sieve number 3, and the specific gravity was estimated at 1.8–2.65. The bed-material gradation was entered and plotted as shown in Figure 7, with D90 at 1.85 mm, D50 at 0.2 mm, and D10 at 0.25 mm. In natural conditions, there is no sharp division between the bed-load

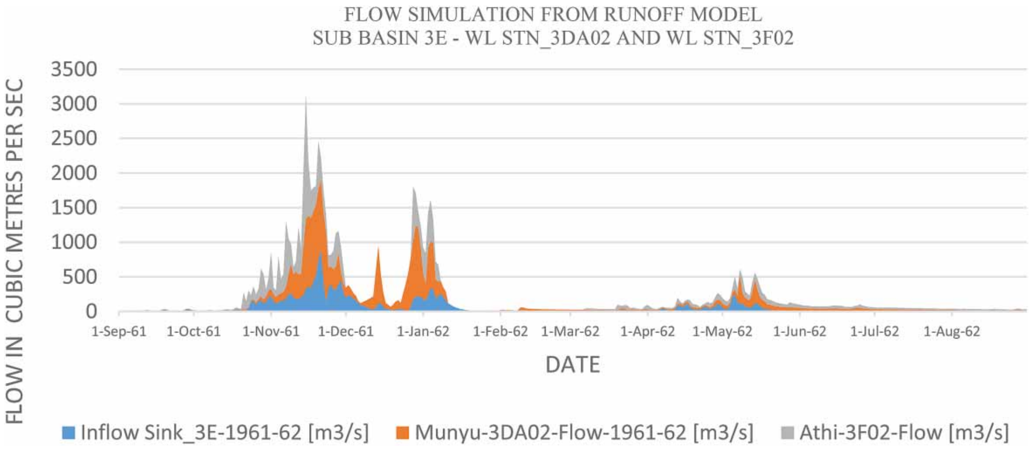

Figure 5 | Flow simulations between 3E-3F02 and 3DA02 and flow correlations between 3F02 and 3DA02 with $R^2 = 0.959$.

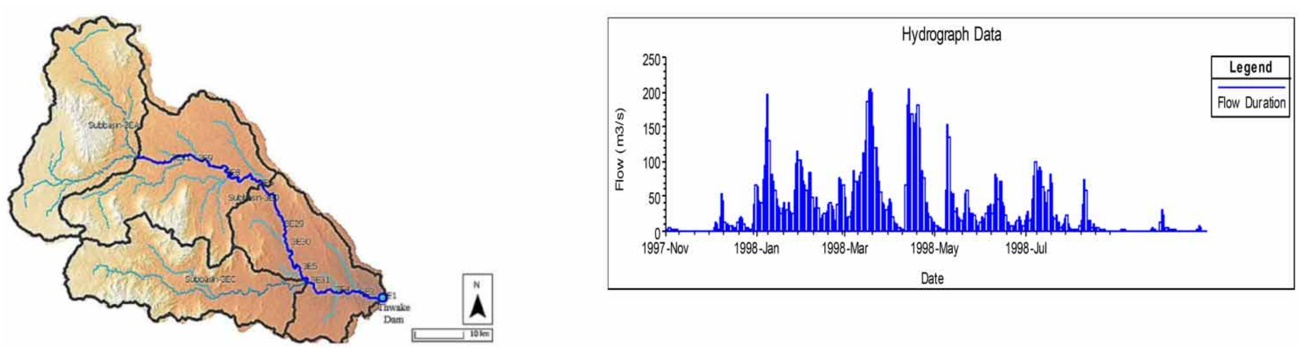

Figure 6 | HEC-HMS reach model and simulated flow of sub-basin 3E.

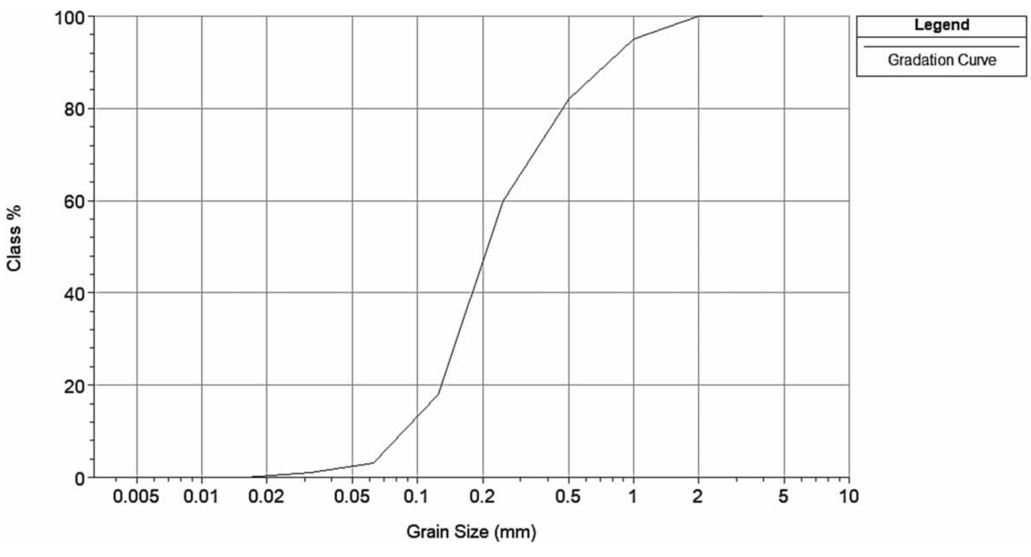

Figure 7 | Bed-material particle-distribution curve.

transport and the suspended-load transport, and it is necessary to define a layer with bed-load transport for mathematical representation.

3.2. Sediment yield rates

With data from the existing Maruba Dam and applying climate-change impact with a 15% increase in precipitation (ISC 2020), the estimated yield is computed at 530 m^3/km^2/year (Luvai *et al.* 2022), equivalent to 1,405 t/km^2/a and 0.724% sediment concentration (Scenario 1). The mass/volume budget gives mass cumulative sediment inflow into the reservoir estimated at 15.8 metric tons of sediment inflow. This represents 2.3% reservoir loss and a useful life under 43 years.

Figure 8 shows cumulative sediment deposition at each cross-section with low curves of red and green representing the initial time-step during simulation and a blue peak at the end of the simulation.

Scenario 2 estimated yields computed at 475 m^3/km^2/year, equivalent to 1,260 t/km^2/a and a 0.65% sediment concentration. The mass/volume budget gives mass cumulative sediment inflow into the reservoir estimated at 14.24 metric tons of sediment inflow. This represents 2% reservoir loss and useful life under 50 years.

Scenario 3 estimated yields computed from RUSLE at 878 m^3/km^2/year, equivalent to 2,327 t/km^2/a and a 1.2% sediment concentration. The mass/volume budget gives mass cumulative sediment inflow into the reservoir estimated at 26.3 metric tons of sediment inflow. This represents 3.8% reservoir loss and a useful life under 26 years (Table 1).

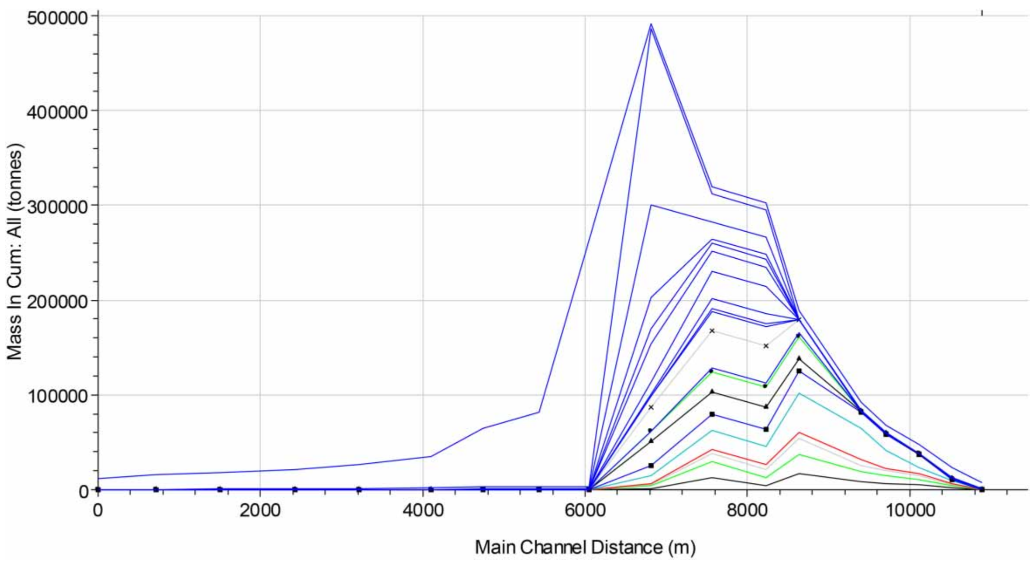

Figure 8 | Cross-sectional mass sediment accumulation in tons.

Table 1 | Summary of reservoir loss calculation

Location	Estimated sediment yields	3A_D Athi River	3E Thwake River	3F02 Thwake Dam
Catchment area (km^2)		7,500	2,800	10,300
Scenario 1 (Maruba bathymetric survey)	Average sediment load *Qs* (Mt/a) Estimated sediment yield (t/km^2/a)	9.9 1,405	5.9	15.8
Scenario 2 (Masinga bathymetric survey)	Average sediment load *Qs* (Mt/a) Estimated sediment yield (t/km^2/a)	9.5 1,260	5.4	14.4
Scenario 3 (RUSLE + climate factor)	Average sediment load *Qs* (Mt/a) Estimated sediment yield (t/km^2/a)	16.5 2,327	9.8	26.3

3.3. Sediment deposition in the Thwake reservoir

Sediment discharge and prediction of deposition into the Thwake reservoir were done using HEC-6, a one-dimensional movable-boundary open-channel flow model, by computing sediment scour and deposition and simulating the interaction between the hydraulics of the flow and the rate of sediment transport. This aspect is fundamental in managing sediment deposition and reservoir operation (Morris & Fan 1998). The model operates on the premise that a state of equilibrium is achieved between the characteristics of the flow and the movement of bed-material transport during each discrete time-step (HEC 2022). Notably, this assumption mirrors the foundation upheld by numerous other sediment transport models that also hinge upon the attainment of equilibrium conditions.

Figure 9 indicates the initial reservoir's minimum operating levels and respective slope plunging into the reservoir, S3, at the minimum operating level. The main dam storage is within a 2 km radius from the dam axis, and the storage volume along Thwake Valley channels (3E) represents 48% of total storage. The reservoir will operate within two levels of 912–887 m, which creates a significant change in Athi River fetches of +6 km compared with Thwake +1 km attributed to the approach slope to the reservoir. This has an impact on the initial and long-term sedimentation of the reservoir and requires an appropriate sediment management plan. The conservation measures will require immediate attention; during reservoir operation, spills and shortages are prone to occur and sometime target releases may not be realized in cases of failed rain. The prolonged drought situations in the region are covered by Ayugi *et al.* (2020) on the impacts of prolonged drought scenarios. It is, therefore, logical to point out that sufficient storage is maintained along Thwake reach, and this was estimated to be about 200 MCM during full supply level and 60 MCM during low supply level. Figure 10 shows the sediment deposition.

Estimated sediment impounded by sand dams and along river channels is enough to silt up the useful storage of the reservoir given sufficient transport conditions. Previous work of ICOLD bulletins (Kondolf *et al.* 2014), displayed in Figure 11, suggests that the dam is in a 'non-sustainable zone'. The type of sediment management actions may result in sustainable or non-sustainable futures. The ratio of reservoir capacity (CAP) and mean annual flow (MAF) for Maruba Dam is 0.21 and the ratio of CAP and mean annual sediment (MAS) is 100–120 whereas for Thwake Dam, those ratios are 0.47 and 70, respectively. Both reservoirs require interventions in managing sediment loads. Potentially sustainable methods recommended to address sediment problems are enhancement of sand-dam construction, check dams, storage operation, and density current venting. In the case above, with no intervention, the CAP/MAF and CAP/MAS ratios decrease and so increase the unsustainability of the reservoir.

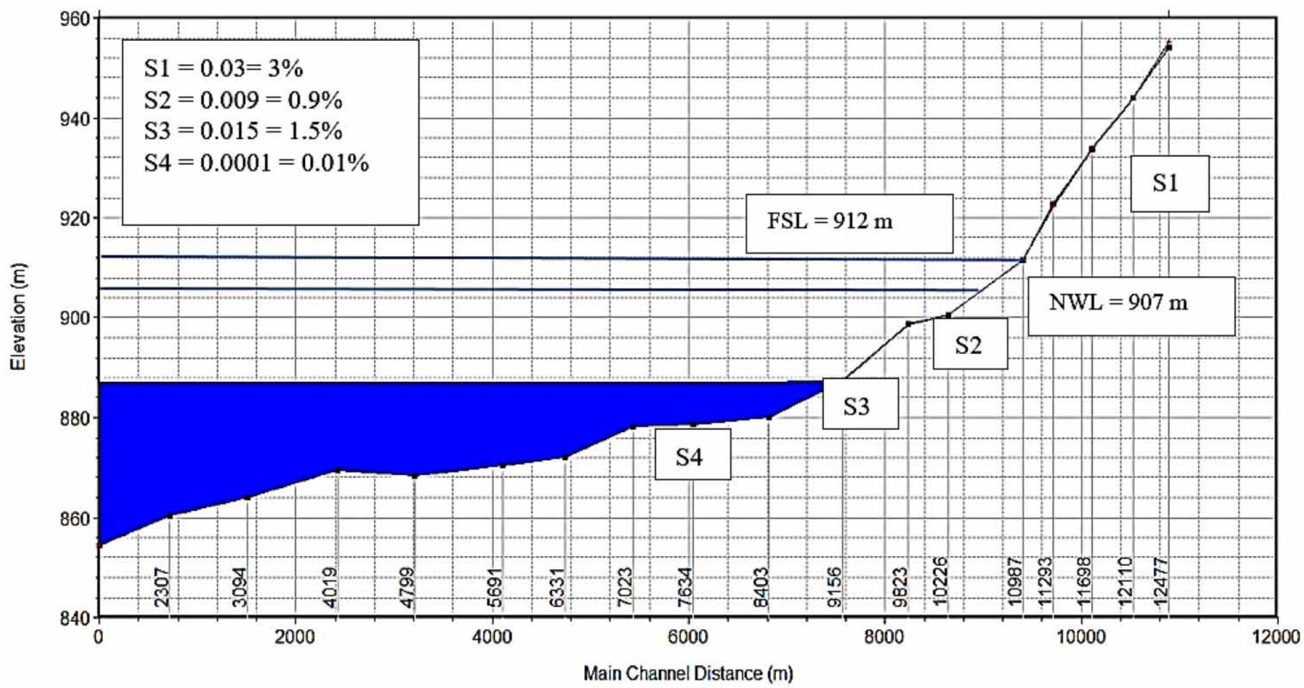

Figure 9 | Initial reservoir operating levels.

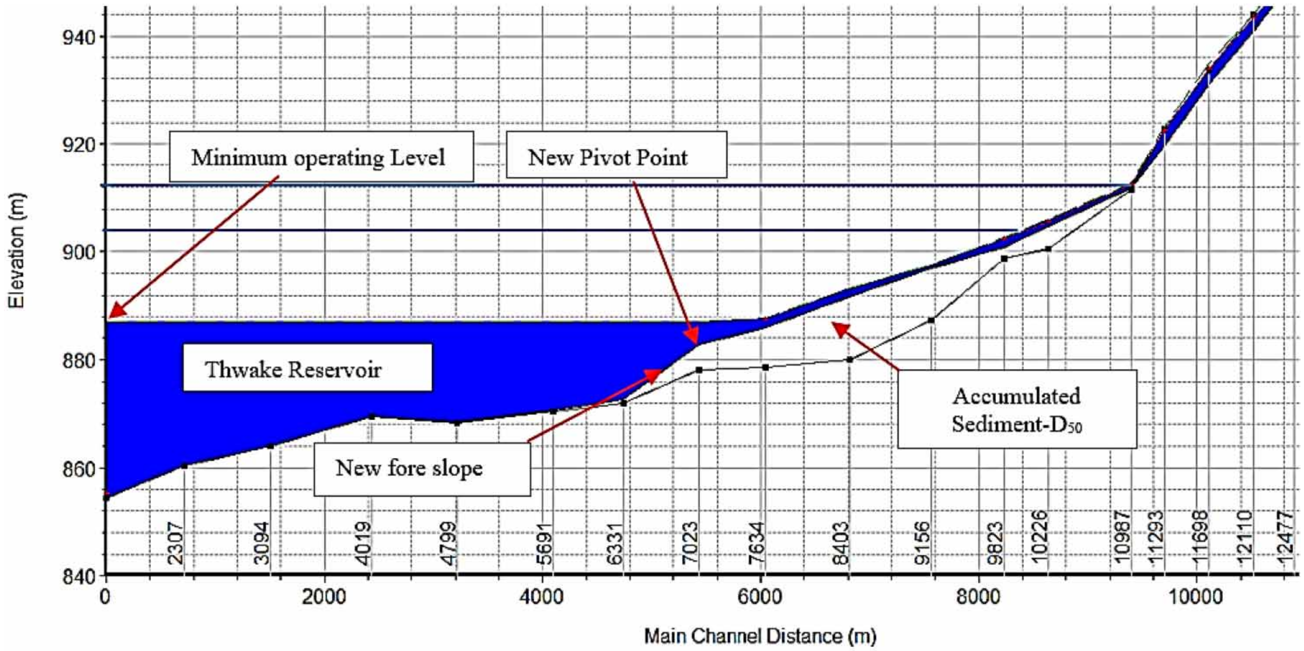

Figure 10 | Predicted delta formation along Thwake reaches 5.4 km.

Therefore, mitigation measures are needed to extend the life of the dam beyond 15–26 years as predicted by the scenarios simulated, especially when considering future climate-change impacts. Several measures are proposed, both social and technical, which will be spearheaded by the Water Resources Users Associations (WRUAs) and responsible institutions.

4. RECOMMENDATIONS

4.1. Sediment management strategies

The findings indicated that sufficient bed material from sub-basin 3E would be deposited into the reservoir, resulting in delta formation approximately 5 km downstream of the tail waters at minimum dam operating level. The mass cumulative sediment inflow from 3E into the reservoir was estimated as between 14 and 26.3 metric tons per annum, representing reservoir loss and useful life under 50 years.

The construction of a submerged check dam is proposed at the delta point to limit progress towards the intake facilities at the embankment of the reservoir. Conservation measures within the sub-basin are recommended such as sand dams. Sand dams, once silted up, can increase the amount of arable land in the region 15-fold (Maddrell 2018). They are each typically about 2 m high, 40–50 m long, and provided with a spillway. The check dams should trap sand but mostly silt based on the hydrological modeling of the sediment routing. The construction of sand dams is suggested to reverse and prevent desertification/land degradation and to mitigate the effects of drought in affected areas to support poverty reduction and environmental sustainability. These interventions can guarantee over 50% reduction in sediment yield translating to the full design life of the reservoir.

4.2. Other measures

The successful adoption of conservation practices is contingent upon a comprehensive consideration of not only their technical efficacy but also the prevailing socioeconomic dynamics. Particularly in the context of the project area, non-governmental organizations (NGOs) have demonstrated adeptness in devising strategies that effectively engage rural populations. In contrast, governmental agencies have at times yielded sub-optimal outcomes. The following features are hallmarks of a successful WRUA participation in the conservation.

The conservation measures proposed are dependent on the slope, current land use, rainfall distribution according to agro-climatic zones, and also whether the conservation works are to be carried out on-farm or off-farm. Hotspots within the catchment to yield an associated reduction in sediment yield were evaluated and it was concluded that 1,400 km^2 of sub-basin 3E

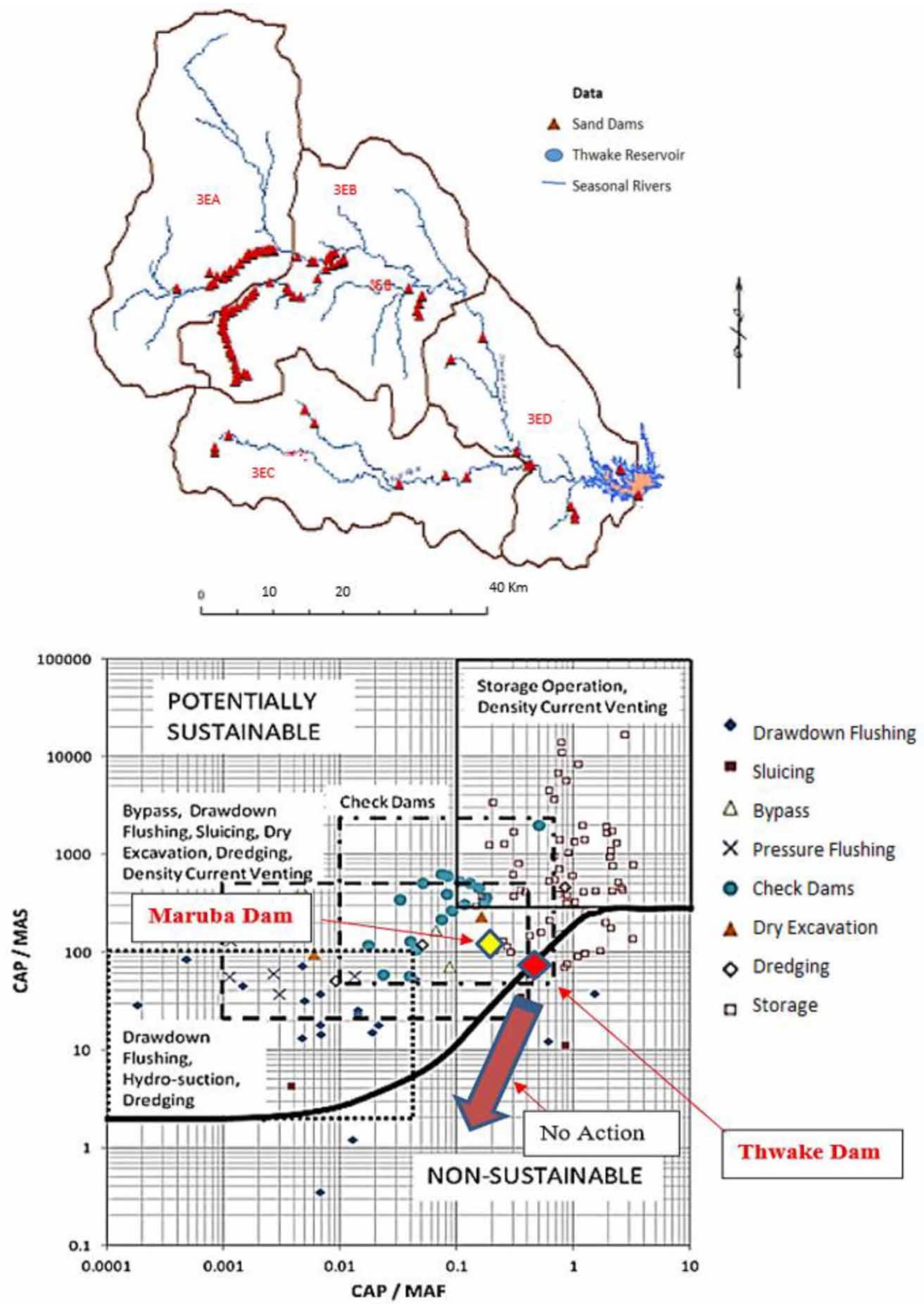

Figure 11 | Existing sand dams in sub-basin 3E and sediment management.

and 3D need intervention to yield a 15%–23% reduction in sediment yield translating to 6–12 years' additional reservoir life (Kiringu *et al.* 2022). Continuous sediment measurements flowing into and out of the reservoir are critical. Remote measurements of sediment loads or concentrations by traditional methods can be expensive and are generally infrequent. Turbidity hydro-acoustic or optical instruments can be used continuously to measure sediment loads entering or leaving the reservoir. These methods are less expensive than direct measurement methods and provide high-resolution time-series data. The advantage of acoustic measurements is reliable data for proper decision-making such as upscaling upstream interventions. Such phenomena as density current/turbidity current may be recorded by the sensors.

The sediment release efficiency of a reservoir is the mass ratio of the released sediment to the total sediment inflow over a specified period. It is the complement of trap efficiency. Empirical relationships have been found to provide reasonable estimates of long-term releasing or trapping efficiency. The effects of reservoir operation are included only to the extent that they are reflected in the selection of the pool volume used in the computations. Judgement is required to adjust these methods to specific conditions (Morris & Fan 1998).

5. CONCLUSIONS

Thwake River exhibits a consistent trend where bed-load transport increases with rising flow; contributions made by ephemeral streams in the transport of bed-load material have indicated the smallest ω^* value observed in the ephemeral stream is approximately 2.5 times larger than the largest value recorded in the perennial stream (Almedeij & Diplas 2005). In the estimation of bed-load transport by desert flash-floods (Reid *et al.* 1996), bed-load sediment transport equations were assessed using field data from desert wadi flash-floods. The Meyer-Peter and Müller equation performs well with median calculated to observed (C/O) ratio of 1.18). In contrast, a study on sediment transport dynamics of the Euphrates River at a thermal power station in Al Anbar province, Iraq (Sulaiman *et al.* 2021), indicated that the Engelund–Hansen formula provided the most accurate predictions for this specific river reach.

The case of Sennar Dam, Sudan, where 29% loss in storage was recorded in just five years (Gismalla *et al.* 2015), points to the importance of reservoir operation rules in sediment management. In consideration of erosion on degraded land, a study of the Hyrcanian forests in Iran (Gharibreza *et al.* 2020) showed 100% efficiency in the restoration of carbon stock over the 30-year span of the reforestation plan that points to the importance of environmental intervention.

This research combines both basin characteristics and application of appropriate transport function in a numerical model to estimate sediment generation, yield, and deposition in the Thwake reservoir. The study contributes to management strategies and understanding of sediment transport dynamics. The estimation of sediment generation and transport using numerical techniques provides flexibility and reliability. Thwake reservoir may not have the 100-year design life as anticipated if there are no interventions on a sediment management plan. All strategies pertaining to sediment reduction should be considered in this case including environmental, social, and structural/physical interventions. Different sediment predictors point to high sediment-load trapped by the reservoir in less than 50 years, estimated in this study at between five and ten years in the worst-case scenario depending on climate predictions.

The financial implications may be unbearable to stakeholders and operators. The immediate concern is to reduce sediment accumulation by carrying out immediate and short-term actions for reservoir-life elongation. This will involve reducing the sediment inflow into the reservoir by putting in place measures to attenuate storm hydrograph and limit conditions for sediment (silt–sand) generation and transport through sediment monitoring plans.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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