RESEARCH ARTICLE

A Novel Approach to Managing Riverine Sediment Deposition in Sand Dam Reservoirs

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ABSTRACT

Sand dams are small, reinforced barriers constructed across seasonal and ephemeral streams which trap water in sediments deposited. For these reservoirs to provide sustainable and dependable water supplies or valuable sand for other purposes, they should primarily fill with coarse sand rather than fine sediments. Excessive accumulation of fine sediments in sand dam reservoirs limits recharge and recoverable water. We describe a novel approach to preventing the accumulation of fine sediments in sand dam reservoirs by geomorphic management of reservoir sedimentation. We propose building sand dams with outlets at the foot of the dam to selectively trap coarse sediments (> 0.125 mm; Rouse number = 2.5) across a range of flows and sediment transport rates. An optimal outlet had an "Eiffel Tower" shape which maintains the desired Rouse number, ensuring finer particles will pass out of the reservoir remaining suspended, while coarser particles settle. HEC-RAS simulations confirm that these designs promote uniform coarse sediment deposition within the reservoir and perform effectively, with minimal deviation from the target Rouse number, with a mean squared error (MSE) of less than 1%. Alternative rectangular and circular base cutouts which can be readily made by embedding culvert pipe also performed well across a wide range of flows. These shapes are simpler to construct and maintain greater structural integrity than the more complex Eiffel Tower (ET) shape. While the ET shape gave the most consistent performance in our tests, simpler designs may offer a better balance between performance, ease of construction, and strength.

1 | Introduction

Sand dams are low-head dams built across ephemeral and seasonal streambeds to enable subsurface storage of water within sediment trapped in the dam's storage volume (Figure 1). Sand dams have improved access to water for millions of people living in drylands (Maddrell 2018) and are increasingly recognized as a promising solution for rural water security in arid regions (Ritchie et al. 2021). Beyond water access, sand dams have also been shown to enhance climate resilience by increasing vegetation recovery and adaptive capacity during droughts (Ryan and Elsner 2016). Their performance is influenced by both physical and social factors, including catchment hydrology, sediment supply, site selection, construction quality, and community management, with sustainable outcomes depending not only on technical design but also on local engagement and implementation dynamics (Ertsen and Ngugi 2021; Ertsen and Hut 2009; Mulwa et al. 2025). However, even traditional indicators failed to reliably predict success, as shown in a survey of 116 sand dams in Kenya where nearly half were dry at the time of assessment despite meeting conventional siting criteria (Ngugi et al. 2020). These inconsistent results highlight the importance of reservoir sediment characteristics in long-term performance. Recent studies have also emphasized the need for improved monitoring approaches to assess sand dam effectiveness over time, including the use of telemetered handpump data to evaluate year-round water availability (Ritchie et al. 2023). For effective interstitial storage of water, sand dam reservoirs should accumulate uniform, coarse sand; fine sediments can reduce porosity and increase inaccessible capillary retention of water (Viducich 2015). An estimated 40%–60% of sand dams in Kenya, where most sand dams are located, are negatively impacted by siltation, or excess silt within their reservoirs (de Trincheria 2016).

1.1 | Sedimentary Processes in Sand Dam Reservoirs

Sand dams create backwater reservoirs, or pools, in which flow depth increases and flow velocity and turbulence decrease relative to the upstream channel, causing sediments in transport to deposit in the reservoir. Deposition typically results in the formation of a Gilbert-type delta of relatively coarse material at the upstream end of the reservoir (Gijsbertsen and Groen 2007). Coarse sediments within the bedload are transported over the delta's topset until they reach the brinkpoint, which is the transition from topset to foreset. Beyond the brinkpoint, the cross-sectional area of flow expands, and flow velocities decrease, causing deposition of bedload sediments within the foreset. The transport and deposition of the bedload cause streamwise delta progradation, eventually filling the reservoir with primarily deltaic sediment. Fine sediments in the suspended load are carried beyond the brinkpoint and into the deeper pool between the delta and sand dam, where they are either deposited in the bottomset wedge or carried downstream of the dam (Reid and Frostick 2011) (Figure 2).

In traditional sand dam designs, unless the reservoir fills with sediment during a single flood event, an open pool of stagnant water is left once the flow ceases. This post-flood pool has significantly lower flow velocities and reduced turbulence, which allows very fine suspended sediments to settle and accumulate in the reservoir. This fine sediment, which might otherwise have been discharged by the dam had flow continued, instead remains in the reservoir and contributes to siltation, which adversely affects drainable porosity and hydraulic conductivity, reducing the recoverable water (Eisma and Merwade 2020; Quinn et al. 2019). Additionally, these temporary stagnant pools create other challenges, such as providing habitats for disease-carrying vectors and posing drowning hazards (Borst and de Haas 2006).

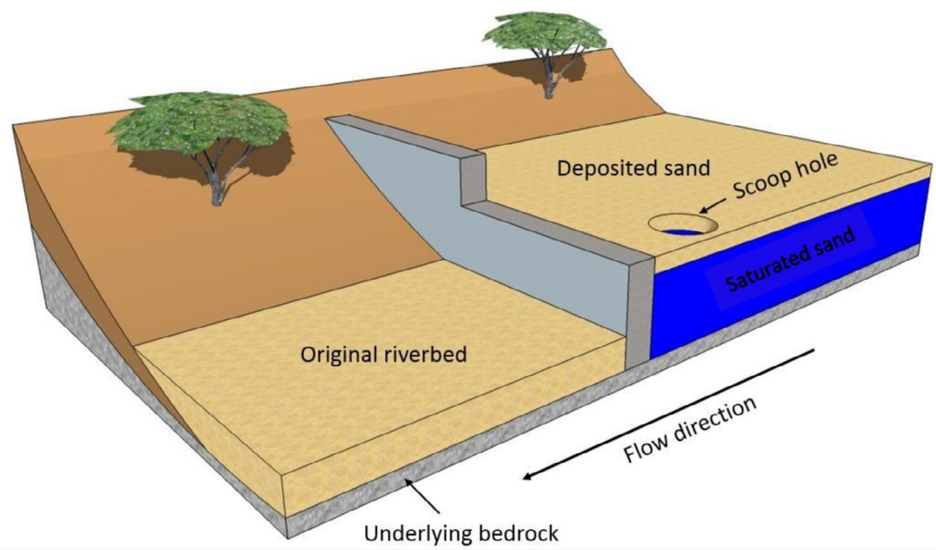

FIGURE 1 | Typical Sand Dam Profile. Seasonal floods deposit sediment upstream of the dam (right side of picture) until the bed reaches the height of the dam spillway. Water infiltrates the deposit during seasonal floods and is stored underground (Viducich 2015).

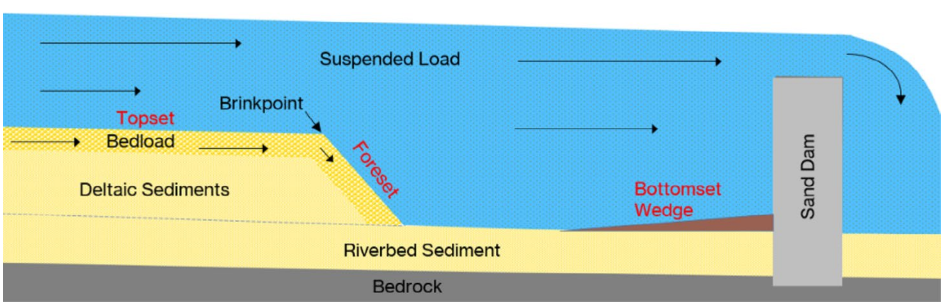

FIGURE 2 | Sediment transport processes in a sand dam reservoir. Bedload sediments are transported over the top of the delta until they are deposited in the foreset, causing progradation of the delta toward the dam throughout the flood. Fine sediments are either carried downstream of the dam or deposited in the pool in between the delta and the dam.

1.2 | Grain Size Distribution and Siltation

The particle size distribution and sedimentary layering or structure within a sand dam deposit are critical factors contributing to its ability to store and yield water. First, a deposit's storage capacity is determined by its porosity. Second, because water is typically extracted from sand dam deposits via hand-dug wells, functional deposits have high specific yields and minimal capillary fringe heights. Thirdly, greater capillary rise permits a greater fraction of the captured water to evaporate from the reservoir's surface. In shallow deposits, this evaporation can be especially significant. Fine sediments contribute to higher capillary rise, exacerbating evaporative losses and supporting phreatophytic plants that further reduce water availability through transpiration. Lastly, functional deposits should have high vertical hydraulic conductivities so that surface floodwaters can quickly infiltrate into the deposit and high horizontal hydraulic conductivities so that stored water can easily flow to extraction points. These deposit characteristics—porosity, specific yield, capillary fringe height, and vertical and horizontal hydraulic conductivity—vary with grain size distribution, and all are adversely impacted by the inclusion of fine sediments (Kitheka 2016; Johnson 1967; Yifru et al. 2021).

While sand dam reservoirs typically accumulate deltaic sediments that are coarser than the native riverbed material, the backwater effect created by the dam reduces flow velocity and turbulence, which leads to the deposition of finer sediments, such as silt and clay, particularly during the early stages of reservoir formation. As flow velocity decreases, fine particles, which are often carried in suspension, begin to settle in the reservoir, contributing to a mix of coarser and finer materials. If a dam's performance is adversely impacted by fines to some critical degree, it is considered “failed” or “silted-up” (Viducich 2015). While there is no universally agreed definition of failure, Castelli et al. (2022) suggest that sand dam functionality should be assessed relative to their intended objectives, such as groundwater recharge, community water supply, or ecological restoration. Nonetheless, siltation is widely recognized as a persistent threat to long-term performance (Borst and de Haas 2006; Maddrell 2018; Viducich et al. 2024).

Thin layers of fines are commonly deposited atop coarser deltaic sediments during a storm's receding limb, when stream competence is minimal, and subsequently covered by coarser deltaic sediments brought by the next flood (Borst and de Haas 2006; Viducich et al. 2024). The thickness of each layer is influenced by factors such as flood depth, flow velocity, and sediment supply, with alternating layers of coarse and fine sediments forming over time. These variations in sediment thickness are determined by the dynamic flow conditions during each flood event, which can change due to differences in storm intensity and riverbed characteristics (Figure 3).

Fine sediments have also been observed in thick layers, sometimes exceeding a meter in thickness (Quinn et al. 2019), in wedge-shaped bottomset beds near the base of the dam (Van den Berg et al. 2007; Viducich et al. 2024), and homogeneously mixed in with coarser deltaic sediments. These fines decrease porosity, specific yield, and vertical and horizontal hydraulic conductivity and increase inaccessible water held within the capillary fringe. It has been estimated that siltation can reduce recoverable water storage by up to 25% (Castelli et al. 2022).

FIGURE 3 | Alternating layers of fine and coarse sediments within a sand dam deposit (Viducich 2015).

1.3 | Previous Approaches to Mitigate Siltation

Sand dam construction has increased since the 1990s, and there is a growing body of literature assessing the benefits of sand dams and recommending where and how to build them—with a focus on preventing siltation. While many studies have emphasized the importance of choosing a suitable site with catchment and riverbed characteristics that indicate transport of relatively coarse sediment during floods (Gijsbertsen and Groen 2007; Ngugi et al. 2020; Nissen-Petersen 2006; Piemontese et al. 2023; de Trincheria et al. 2015; Yifru et al. 2021), other research has focused on dam design and construction methods.

To mitigate siltation, Wipplinger (1953) promoted the staged-construction method: “A weir is raised in stages so that velocities of flow through the basin are appreciable and most of the fine silt is carried over the dam wall, whereas the coarser fractions are retained.” Several recent studies echo this recommendation, citing the high prevalence of “silted-up” sand dams in Kenya as a key reason to adopt the staged-construction method (Nissen-Petersen 2011; Maddrell and Neal 2012; de Trincheria et al. 2015; de Trincheria 2016; de Trincheria et al. 2018). Recent work has also explored innovative construction strategies, including multi-stage and hybrid dam systems designed to improve resilience and reduce maintenance burdens in vulnerable regions (Chung et al. 2025).

Traditional staged sand dam construction, which tends to produce shallower, faster flow in the reservoir, is currently promoted as a best practice for preventing siltation (Figure 4). Viducich et al. (2024), however, used one-dimensional unsteady numerical

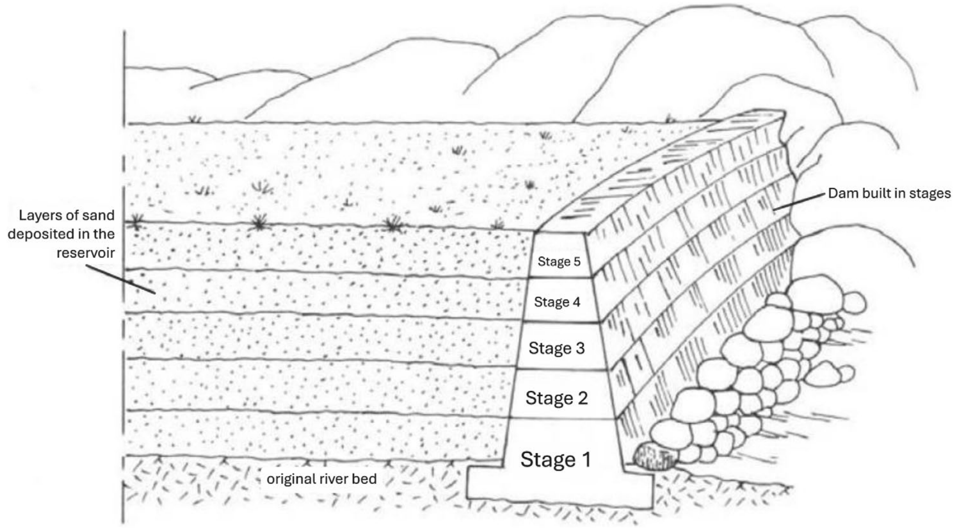

FIGURE 4 | A sand dam constructed in five stages. Short stages create a shallow, rapid flow in the reservoir, helping prevent the accumulation of fine sediments (Nilsson 1988).

flow simulations to quantify the sensitivity of sedimentation processes to sand dam crest height. Floods were simulated at sand dam sites in Kenya using surveyed channel geometry data, crowd-sourced hydrograph data, and various crest heights reflecting as-built and test designs. The modeling results indicated that the staged-construction method—where the height of a central spillway is incrementally increased over time—may be useful for limiting siltation at some sites by maintaining sufficient shear stress in the reservoir to suspend and transport fine sediments downstream. While the staged-construction method may be effective, it typically results in substantial additional material and labor costs due to the multiple mobilizations for construction. This limits its applicability in undeveloped rural settings. Additionally, traditional methods risk creating open-water pools and allowing fine materials to settle near the dam wall, reducing reservoir efficiency (Viducich et al. 2024).

In contrast, this paper focuses on outlet design rather than dam height staging. The importance of outlet configuration was first emphasized by Baurne (1984). He suggested, "In remote areas where the yearly addition of stages is difficult due to lack of skilled workers and suitable construction material, dams could be built in one step. In this case the dam should be built to its full height, leaving a large V-shaped or rectangular notch in the dam wall to be filled as the dam itself fills with sediments" (Baurne 1984). Both Baurne's suggested approach and the novel approach described in this paper are similar in that most major dam construction happens in a single stage, with only the filling of the outlet necessary as the second step. With only two construction steps, this approach is cheaper, more practical, and thus more likely to be implemented than the staged construction method.

1.4 | Motivation and Objective

This study was motivated by the question: Can we prevent siltation of sand dam reservoirs through alternative designs that minimize these downsides while maintaining coarse sediment deposition? We propose that siltation can be prevented by constructing sand dam reservoirs with Eiffel Tower-shaped (ET-shaped) outlets that maintain a minimum bed shear stress sufficient to prevent silt deposition across a range of low to moderate streamflow, when siltation is highest and fine sediment can be selectively flushed. Bed shear stress generates vertical turbulence, which drives sediment suspension (Ralston and Stacey 2006). ET-shaped outlets establish a stage-discharge relationship in the channel such that, regardless of flowrate, shear stress in a reservoir is sufficient to keep unwanted fine sediments in suspension and washed downstream while allowing sand to accumulate. Once the reservoir is nearly full of sediment, the outlet would be sealed to make the dam impermeable.

Furthermore, the ET-shaped outlet design is specifically aimed at preventing fine sediment deposition during low flow conditions, such as the receding limb of larger flood hydrographs. Unlike top-notch outlets, which are primarily used to maintain flow during high-flow events and keep sediment in suspension, the ET-shaped outlet's role is to selectively retain coarse-grained sand while preventing fine sediment from settling in the reservoir. This selective sediment retention feature enhances the long-term efficiency of the dam by ensuring fine sediment remains suspended during low flows, when stream velocities are reduced, and the outlet's influence on fine sediment transport is minimal. By focusing on this aspect of fine sediment management, we seek to improve sand dam performance and minimize the challenges posed by siltation in dryland water storage systems.

This paper presents the process and geomorphic theory behind the idea of building sand dams with ET-shaped outlets, which selectively trap coarser sediment by maintaining a constant Rouse number. A preliminary assessment of this novel approach, focusing on grain size-selective trapping, was conducted using the US Army Corps of Engineers Hydraulic Engineering Center's River Analysis Software (HEC-RAS).

2 | Methods and Data

This paper seeks to identify a dam outlet shape that allows fine sediments with a median grain diameter (D_{50}) below a desired value to pass downstream for a range of flow magnitudes. To this end, various aspects that can affect sediment deposition, such as site selection and riverbed characteristics, were considered. After defining the minimum desired particle size, sediment transport analysis was conducted based on the Rouse number. Subsequently, open-channel hydraulic calculations were performed using the "universal wall function" or law of the wall (Alfadhli et al. 2013). The optimal outlet geometry was determined by converting pressure head to velocity head at the plane of the outlet, a method commonly employed in weir equations. This section describes the methodology, including comparison of different outlet designs and validation using hydraulic numerical modeling.

2.1 | Minimum Desired Particle Size

To ensure effective water storage in sand dam deposits, we must select a minimum acceptable particle size that prevents excessive fine sediment accumulation. Finer sediments, particularly silts and clays, reduce the drainable water capacity by increasing capillary forces, which makes it harder to extract stored water under gravity. For instance, a deposit with a dominant grain size of 0.125 mm can have approximately 50 cm of capillary fringe (Schroth et al. 1996), meaning that the water contained in the pores of media in the bottom 50 cm of the dam fill would be expected to be unavailable. In a typical sand dam with a depth of 2–4 m, this could reduce the recoverable storage by 10%–25%. This estimate assumes a uniform cross-section; in practice, sand dam deposits often taper toward the bottom, so the corresponding volumetric loss would likely be less than the percentage loss in depth. From basic capillary theory we know that deposition of yet smaller particles proportionally increases capillary fringe height, while a broader particle size distribution results in lower porosity and lower specific yield. The inclusion of fines within a matrix of coarser sand can reduce porosity by up to 50% (El-Husseiny 2021; Beretta and Stevenazzi 2018).

Given these considerations, we define 0.125 mm as the minimum desired particle size for our study. This threshold was selected because it represents a practical boundary between sand and finer particles, helping to limit excessive silt and clay retention in the reservoir (Maddrell and Neal 2012; Vanoni 2006; Viducich 2015). In settings with a coarser sediment supply, a larger minimum particle size may be more appropriate to maintain homogeneity in the deposit. The 0.125 mm threshold should be viewed as strictly a matter of having a concrete set of results in this paper as the methodology can easily be adjusted to retain any particle size of interest.

2.2 | Sediment Transport Analysis

Our sediment transport analysis builds on Viducich et al. (2024), who used the dimensionless Rouse number (R_0, Table 1) to predict sediment transport modes and particle fate across a range of flow depths and velocities.

The Rouse number, R_0, is the ratio of settling velocity, w_0, which is constant for a given particle size, to the product of shear velocity, u^*, and the von Karman constant, k (Equation 1).

TABLE 1 | Particle's Rouse numbers for different modes of transport (Whipple 2004).

Rouse number	Mode of transport
0–0.8	Wash load
0.8–2.5	Suspended load
2.5–7.5	Bed load
> 7.5	At rest

Shear velocity is an expression of bed shear stress with units of velocity and is equal to the square root of bed shear stress, τ_b, divided by fluid density ρ (Equation 2) (Chanson 2004). The relationship between Rouse number and mode of transport varies slightly throughout the literature; however, our selection of 2.5 as the threshold Rouse number separating bedload and suspended load aligns with all sources identified (Johnson and Whipple 2010; Pekker 2017; Van Rijn 1993; Vonkeman 2019).

$$R_0 = \frac{\omega_0}{k * u^*} \tag{1}$$

$$u^* = \sqrt{\frac{\tau_b}{\rho}} \tag{2}$$

Particles with a Rouse number of 2.5 or less remain mobile and are transported through the dam, whereas those with a Rouse number greater than 7.5 are expected to deposit in the reservoir. Values between 2.5 and 7.5 may travel either as suspended load or as bedload, depending on local flow conditions. The Rouse number increases toward the dam as flow expands, reducing velocity and shear stress. This means coarser particles transported in suspension upstream are more likely to deposit before reaching the dam, supporting the assumption that only particles with $R_0 \leq 2.5$ at the dam will pass through. Given the square root relationship in the Rouse number equation, tripling R_0 from 2.5 to 7.5 requires a ninefold increase in settling velocity, suggesting that particles larger than ~1 mm will be retained within the reservoir. This highlights the selective trapping mechanism, where particles larger than the target grain size are retained upstream of the outlet.

While our sediment transport analysis method involves simplifying assumptions and neglects delta progradation, it is appropriately conservative. Flow over a delta is relatively shallower and faster than flow at the same location in a delta-free reservoir (Jobson and Froehlich 1989) as illustrated in Figure 2. Therefore, the Rouse number of a particle as it is transported over the topset of a delta is lower (i.e., the particle is more mobile) than at the same location in a delta-free reservoir—this provides the mechanism for transporting bedload to be deposited on the foreset. By ignoring delta progradation, we overestimate effective Rouse numbers and underestimate the size of the particles that will be deposited in the reservoir. That is, we believe that this method may be even more effective at promoting exclusive deposition of coarse sediment than our results indicate. However, consideration of the source material is warranted: Rouse numbers must be low enough in the flow expansion area to ensure sedimentation.

2.3 | Determining Optimal Outlet Geometry

Strategically designed outlets can affect a reservoir's stage vs. discharge relationship, thereby changing sediment transport dynamics and deposition. We seek an outlet size and shape which would create a favorable depositional condition near the dam wall, but not so close to the outlet that its influence distorts flow dynamics. The goal is to maintain shear stress that is sufficiently high to pass unwanted fines and sufficiently low to trap desirable coarse material. This outlet will create an environment where bed shear stress is sufficient to establish a shear velocity that maintains a Rouse number high enough to keep particles with diameters of 0.125 mm or smaller in suspension, thereby preventing their deposition. Coarser particles, however, will accumulate regardless of stream flow conditions.

Flow in reservoirs is non-uniform, with deepest near the dam and shallowest at the upstream end of the pool, causing shear stress, and consequently, the Rouse number to vary longitudinally. As a delta begins to form, Rouse numbers are typically lowest over the topset, where sediment is relatively mobile. Toward the deeper areas near the dam, beyond the foreset, Rouse numbers increase, indicating reduced sediment mobility. During periods of relatively constant flow, additional sediment accumulation over the topset slows but does not entirely cease, as some bedload continues to settle while other particles remain mobile. Meanwhile, the lowest shear conditions occur beyond the foreset, where the bottomset accumulates. This location is the design-limiting factor, as it is where we seek to avoid accumulation of silt and clay. Hence, we focus our analysis on the conditions found in flow above the bottomset where we seek to establish the favorable depositional environment, with $R_0 < 2.5$ for a 0.125 mm particle, washing silt and clay sized material out of the reservoir.

The process detailed below assumes laterally uniform (one-dimensional) flow with the same flow velocity across each cross-section. It also accounts for vertically non-uniform varying hydraulic conditions along the channels upstream in the context of one-dimensional flow. Furthermore, we assume that the vertical velocity profile described in the following section is valid throughout the system. While these assumptions ignore some complexities and heterogeneities of actual reservoirs, they provide a useful approximation of reservoir hydraulics (Bonakdari et al. 2008).

2.3.1 | Process to Determine Optimal Outlet Geometry

The optimal outlet shape was determined using equations that relate depth, flow rate, bed shear stress, and particle mobility. First, the settling velocity of the particle of interest was calculated using Equations (1–3). Since settling velocity, the particle drag coefficient (Equation 4), and the particle Reynolds number (Equation 5) are interdependent, we solved these equations simultaneously (Chanson 2004).

$$\omega_0 = -\sqrt{\frac{4gd_s}{3C_d}(s-1)} \tag{3}$$

$$C_d = \frac{24}{Re} + 1.5 \tag{4}$$

$$Re = \frac{\omega_0 d_s}{\upsilon} \tag{5}$$

In these equations ω_0 is settling velocity, g is gravitational acceleration, d_s is particle diameter ($d_s = 0.125$ mm), s is the ratio of particle density to water density (s = 2.65 for quartz sand (Gibbs et al. 1971) and is assumed here), C_d is a drag coefficient, υ is the kinematic viscosity of water (1 mm^2/s at 20°C) and Re is the particle Reynolds number.

Next, the shear velocity required for favorable deposition (u^*_G) was calculated rewriting Equation (1) to solve for the required shear velocity to produce a Rouse number of 2.5 result in Equation (6):

$$u^*_G = \frac{\omega_0}{R_0 * k} = \frac{\omega_0}{2.5 * k} \tag{6}$$

k is the von Karman constant (0.4), and other parameters are as previously defined.

Equations (7) and (8) were used to define the relationship between u^*_G, volumetric flow rate (Q), and flow depth (y) in the upstream pool. Equation (7) is a semi-empirical equation describing the velocity profile for flow in an open channel with a hydraulically smooth bottom (Alfadhli et al. 2013).

$$\frac{u(y)}{u^*_G} = \frac{1}{k} ln\left(\frac{y u^*_G}{\upsilon}\right) + 5 \tag{7}$$

In this equation, $u(y)$ is flow velocity at depth y, and 5 is an empirically derived constant. Integrating Equation (7) over depth from the bed to the water surface gives Equation (8), which describes the relationship between depth-integrated velocity and discharge in the upstream pool:

$$Q = \frac{b}{k}\left(5y + y * \left(ln\left(\frac{u^*_G y}{\upsilon}\right) - 1\right)\right) \tag{8}$$

By solving for the flow depth required to obtain a Rouse number of 2.5 over a range of flow rates, we establish the optimal stage-discharge relationship at the dam, which is then used to derive the outlet shape. While the Rouse number at the outlet itself may differ due to local hydraulic conditions, our focus is on optimizing sediment deposition upstream where the reservoir's sediment dynamics are most critical. We assume that by optimizing the Rouse number upstream, we will achieve the desired sediment management effects throughout the reservoir. Flow rate and outlet shape were related by estimating the flow velocity at the plane of the outlet to be that which could be obtained by the hydrostatic pressure, which simplifies the approach by excluding dynamic energy components like approach velocity. The outlet shape was constructed from low flow to high flow computationally by adjusting both width and height of the aperture so that the Rouse number was precisely 2.5 at all flow rates. The process began with an initial defined channel width of 8 m, used to estimate mid-depth flow conditions upstream of the dam. For each discrete flow

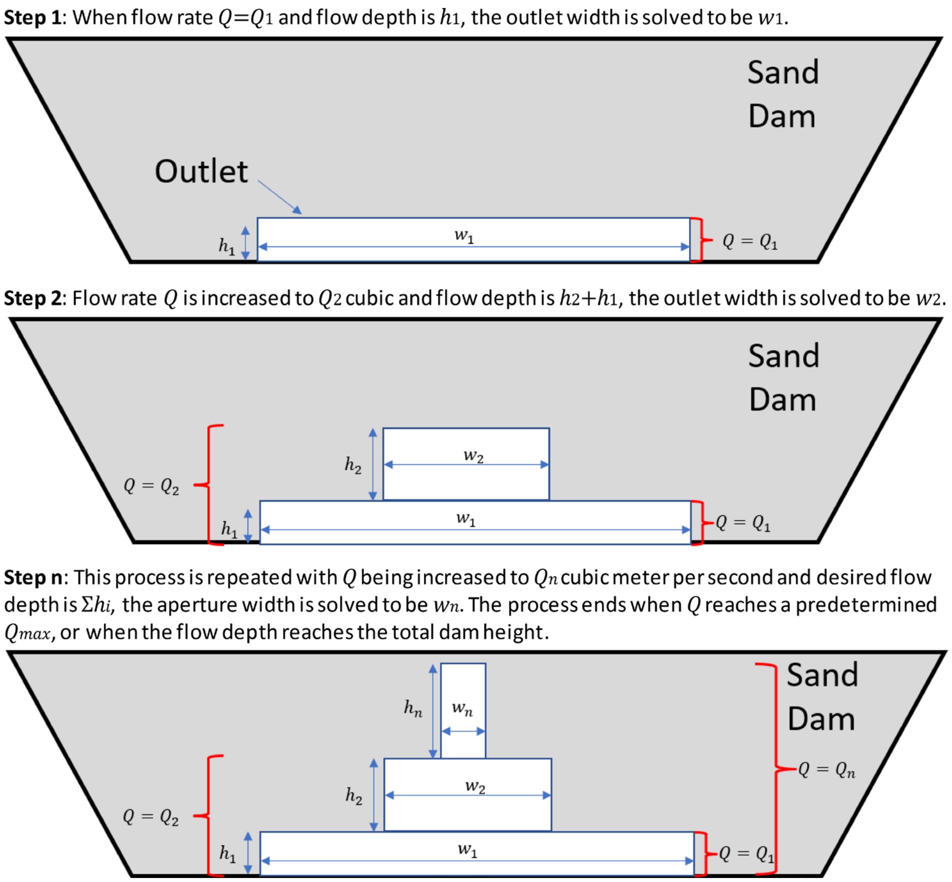

FIGURE 5 | Flowchart for finding optimal outlet geometry.

rate, the required outlet dimensions were calculated to ensure the appropriate discharge could pass while maintaining the desired sediment transport conditions. This resulted in a series of stacked rectangular openings, where each step was designed based on the flow rate and sediment transport criteria (Figure 5).

To refine the design, we conducted a sensitivity analysis to determine the appropriate flow rate increments used in computing outlet dimensions, aiming to balance computational efficiency with design accuracy. Step sizes of 0.1, 0.25, 0.5, and 1 m^3/s were tested. Small changes in flow rate produced minimal differences in outlet width, while the smallest step size of 0.1 m^3/s caused instability at lower flow rates, likely due to numerical sensitivity when solving for flow depth and outlet width. Based on these results, a step size of 0.25 m^3/s was selected to balance stability, accuracy, and smooth transitions in the outlet shape. Coding these calculations in MATLAB allowed creation of a smooth "ET shape" (Figure 6a) rather than a stepped, tiered structure (Figure 5). Full details of the sensitivity analysis are provided in the Supporting Information.

To address structural and construction considerations, the outlet shape was modified from a pure ET form to a more practical design with a narrower base for dam stability and a simplified geometry using straight-line approximations for ease of construction.

2.3.2 | Stage-Discharge Relationships for Optimized Outlet Geometry

As described in Section 2.3.1, open channel hydraulic calculations in which pressure head was converted to velocity head were used to determine the ET outlet shape. This method, however, does not account for shear losses or flow convergence effects, leading to an overestimation of the discharge at a given stage relative to the actual stage-discharge relationship for the unadjusted ET outlet shape.

To refine the design, we conducted preliminary HEC-RAS simulations to estimate flow depths and evaluate the discharge capacity of the unadjusted outlet shape. These simulations revealed that the theoretical calculations overpredicted discharge due to unaccounted hydraulic effects. To correct for this discrepancy, we increased the width of the ET outlet by 40%, ensuring a closer match between the simulated and target stage–discharge relationships.

Figure 7 presents the stage-discharge relationships from HEC-RAS for the following outlet geometries:

- Unadjusted ET shape: The initial curved design derived directly from the target Rouse number relationship.
- 40% wider ET shape, hereafter referred to as just "Eiffel Tower" (ET): A version of the unadjusted ET widened to better align with HEC-RAS flow outputs.

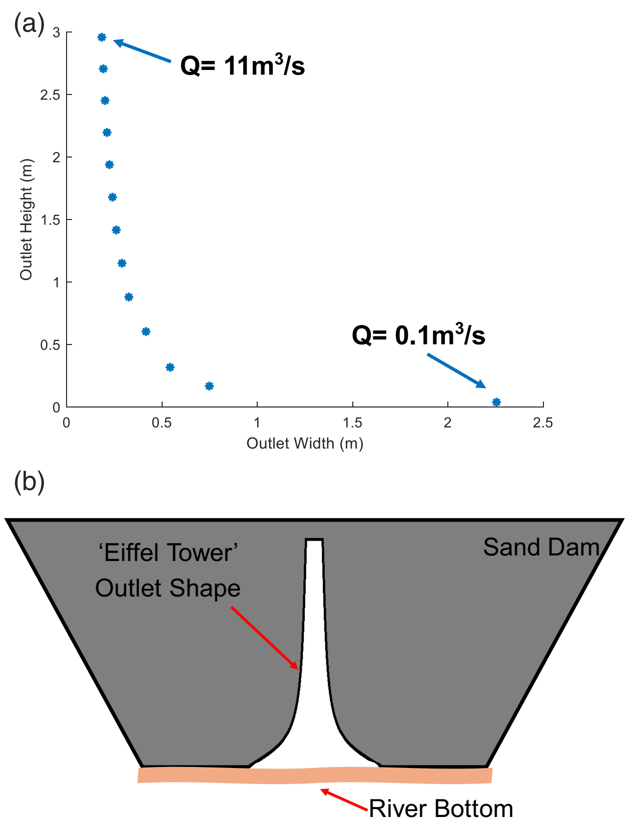

FIGURE 6 | (a) The aperture geometry obtained from MATLAB with only the right half of the outlet shape shown (outlet is symmetric), (b) Sand Dam with an "Eiffel Tower"-shaped outlet.

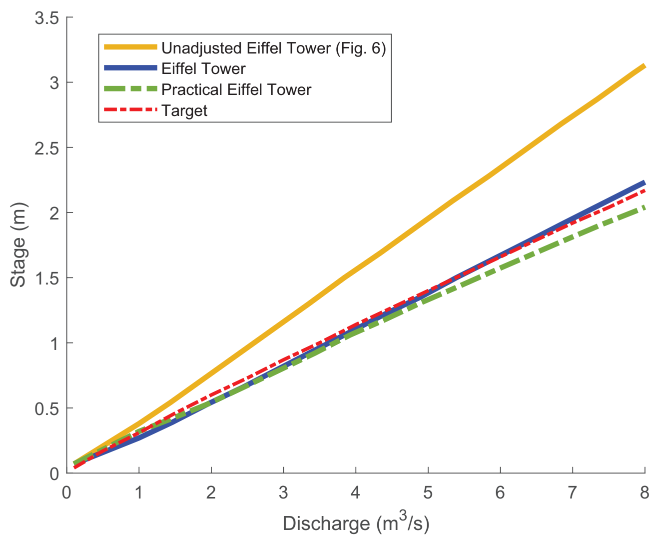

FIGURE 7 | Stage discharge relationship of the Eiffel Tower shape with and without the 40% width adjustment employed to correct for convergence and shear loss terms.

- Practical Eiffel Tower shape (PET shape): A simplified version of the widened ET that uses straight segments instead of curves and incorporates a narrower base to facilitate construction.
- Target stage-discharge curve: Computed independently using open-channel hydraulic equations based on Rouse number criteria.

Over the full range of discharges, the stage-discharge of the adjusted ET outlet matched the target relationship to within 3% (Figure 7).

2.4 | HEC-RAS Modeling

One-dimensional (1D) unsteady numerical modeling was conducted using HEC-RAS 5.0.7 to calculate the Rouse number for 0.125 mm diameter particles over varying discharges as a function of outlet geometries. Notably, the total areas of the outlets were kept constant at 3.5 m^2, derived from the optimized outlet shape determined in Section 2.3.2, to specifically assess the influence of different outlet shapes, rather than outlet areas. Figure 8 illustrates the main outlet shapes tested in the HEC-RAS model; more detailed dimensional drawings of each outlet are provided in the Appendix under HEC-RAS Geometry Outlets.

2.4.1 | Model Development

The model was based on a simplified river reach inspired by a sand dam site in Kenya (Viducich 2015), with a channel slope of 0.005 and a rectangular cross-section. The riverbed was modeled with a constant width of 8 m. Cross sections were spaced every 2.5 m along the 210-m-long channel, with the sand dam located 50 m upstream of the model boundary. A sensitivity analysis was conducted to test the sensitivity of the average velocity of flow in the channel to cross-section spacing, comparing the 2.5-m and 5-m spacings in HEC-RAS simulations. The results showed less than a 5% difference in model outputs across the entire channel, indicating that the 2.5-m spacing is sufficient to capture the key flow and sediment dynamics without requiring smaller spacing.

The river reach was constructed to simulate flow conditions based on field observations by one of the authors (Viducich 2015), with channel characteristics reflecting typical flow patterns and hydraulic behavior. A single Manning's n value of 0.025 was applied to the bed throughout the channel, representing the flat, sandy riverbed (Chow 1959). The sand dam was modeled as an inline structure in HEC-RAS using the "Weir Shapes" sheet in the geometry data, where a v-notch weir was added as an inline structure and specified with field-measured dimensions. The outlets, represented by bottom openings of various shapes, were modeled as a bridge/culvert using the "Deck/Roadway" option in HEC-RAS. This approach was chosen because the weir option did not allow for the creation of an opening at the bottom of the structure. Careful attention was given to ensure that using the bridge option did not introduce unrealistic hydraulic behavior.

2.4.2 | Simulation Procedure

The unsteady flow simulations were designed to replicate varying flow conditions by applying an upstream input hydrograph that increased from 1.0 to 11 m^3/s in discrete 30-min increments and a normal depth downstream boundary. This approach functioned as a series of steady-state simulations, allowing the model to stabilize at each flow step before progressing to the next. The outflow hydrograph at the weir was examined to confirm that the intended flow magnitudes were

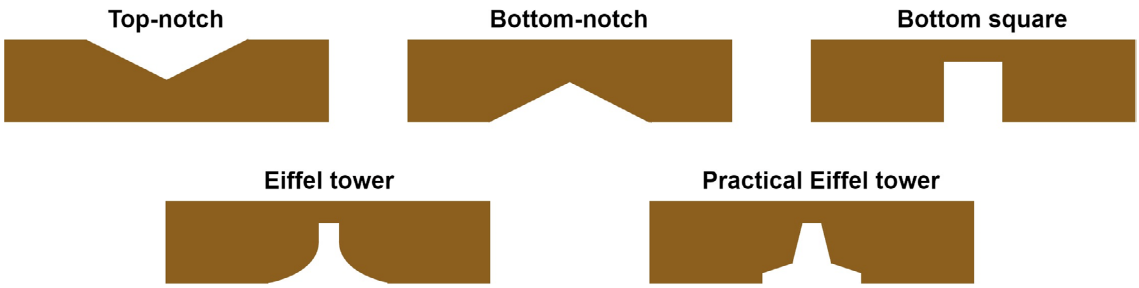

FIGURE 8 | Diagram of outlet structures studied.

achieved at the structure. The upper limit of 11 m^3/s was established to prevent dam overtopping, which would submerge the outlet and induce pressure flow conditions. This range of flow variation allowed for the assessment of sediment transport mode across different discharges, particularly during lower flow conditions when the outlet is likely to be active. However, it is recognized that larger flow events, which could exceed 11 m^3/s, may be important for sediment transport into the reservoir.

The model was run with a time step of 1 s and output intervals of 30 min. Sediment transport modes were evaluated based on the hydraulic results modeled in HEC-RAS, specifically using bed shear stress values at each cross-section, as described in Equation (2). Settling velocity was calculated for 0.125-mm particles using Vanoni (2006) equation, which was adapted to account for specific properties of the sediment used in this study, including particle density and size. With these velocities, Rouse numbers were computed at each cross-section and for each time step using Equation (1), aligning with the model's output intervals. The results were analysed to compare sediment behavior under different outlet configurations, providing insight into their performance in controlling sediment deposition upstream of the dam.

3 | Results

Results from HEC-RAS simulations showed that the ET-shaped and the PET-shaped outlets successfully maintained a constant Rouse number of 2.5 across the entire range of modeled flows at a location 20 m upstream of the dam (Figure 9a).

The top-notch outlets, commonly referred to as v-notch weirs, did not provide favorable depositional conditions at low flow rates, with Rouse numbers approaching 20 at low flow. This would be expected to result in the deposition of fines, which primarily occurs during the receding limb of flood events following rainfall, when flow rates are low (Section 1.3). On the other hand, all the outlets positioned at the base of the dam produced relatively consistent and desirable results across the range of the modeled flows. The ET and PET-shaped outlets were most ideal because they maintained Rouse numbers very close to the target suspension threshold of 2.5 across all tested discharges, ensuring stable and predictable sediment transport behavior. In comparison, the bottom-square and bottom-notch outlets produced more variable Rouse numbers, particularly at lower flows, and thus were less effective at maintaining consistent transport conditions; however,

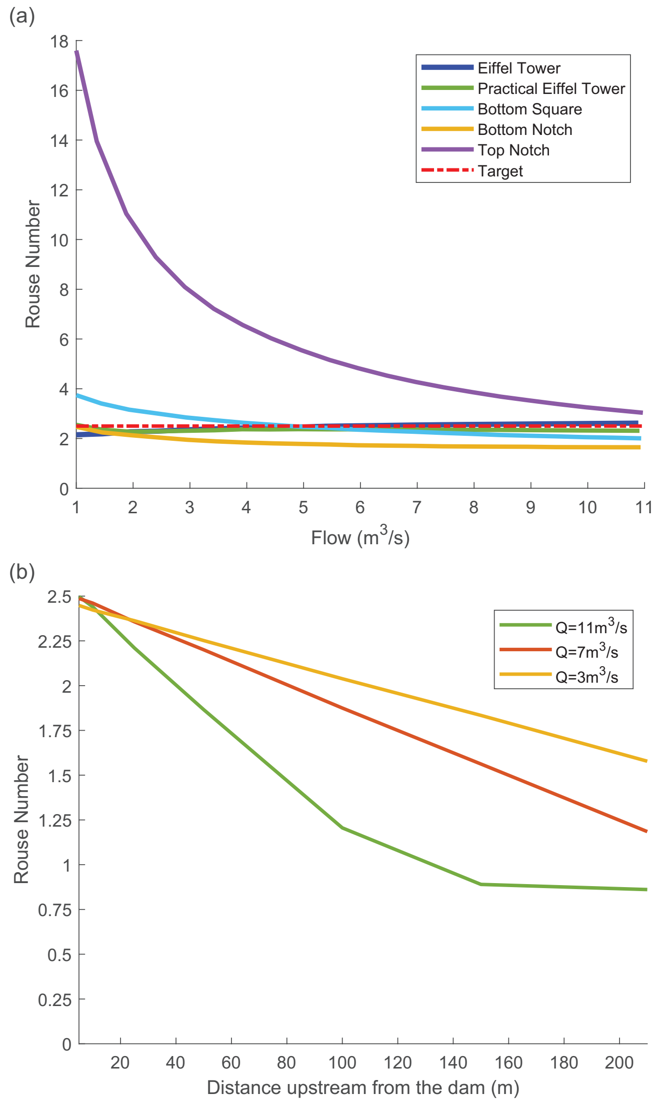

FIGURE 9 | (a) Rouse number vs. flow rate with ideal favorable deposition shown with red line (for a 0.125 mm-diameter particle 20 m upstream of the dam), (b) Rouse numbers with the Eiffel Tower outlet in place plotted against distance upstream of the dam for various discharges. The right axis indicates the minimum particle size expected to move as bedload, corresponding to each Rouse number.

variability still remained less than a factor of 2 across the tested flow range.

Figure 9b shows the variation in computed Rouse numbers for a 0.125-mm particle throughout the reservoir for three representative flows. The Rouse number remains below 2.5 across all modeled flow conditions, indicating that finer particles—smaller than the target sand size—are likely to remain in suspension and may not settle before reaching the dam outlet. This suggests that the reservoir effectively excludes these finer sediments under the modeled conditions, while coarser sand is expected to deposit upstream. The right axis translates Rouse number values into the minimum particle size expected to travel as bedload, providing a sediment size threshold above which deposition is favored.

4 | Discussion

4.1 | Comparison of Outlet Structures

The HEC-RAS results informed key adjustments to the theoretical outlet design, revealing that an increase in outlet size by approximately 40% was necessary to achieve the target hydraulic performance. While this represents a significant modification, the general shape of the outlet derived from mathematical calculations (Section 2.3.1) remained consistent with the optimal configuration identified in the simulations—namely, maintaining an opening at the channel bed to promote the selective passage of fines while retaining coarser material.

Initial calculations were performed to establish a theoretical baseline for the ideal outlet shape, considering factors such as flow capacity and sediment transport. These calculations helped us narrow down the range of potential outlet shapes, ensuring that the options modeled in HEC-RAS were both hydraulically efficient and suitable for further analysis. By using HEC-RAS to simulate different outlet geometries, we could assess how each shape performed under various flow conditions, optimizing the design to minimize siltation while maintaining optimal hydraulic conditions.

It appears that the high Rouse number computed from the use of top-notch outlets supports the field observation that current practice of building sand dams with shallow spillway notches at the top of the dam, or without notches at all, leads to the accumulation of fines. On the other hand, having a properly sized outlet at the bottom of the dam, essentially regardless of its shape, allows smaller particles to wash out. In this regard, our method illustrates how the shape of the outlet in the dam greatly influences sediment deposition, with a particular emphasis on the importance of the bottom opening.

Another contribution of this work is to show that constructing a sand dam with an ET-shaped outlet maintains relatively stable bed stress near the dam during low flows. While Rouse numbers do vary with flow and spatially across the reservoir, outlets positioned at the base tend to produce lower and more stable Rouse numbers in the critical area near the dam. This suggests that such designs can help ensure fine material is consistently conveyed through the most deposition-prone zone over a range of low flows. Practically speaking, it would be simpler to construct a triangular, square, or circular opening than the construction of the optimal ET shape. Thus, the performance of practical opening shapes is worthy of further investigation to develop low-cost, optimal outlet guidelines for sites deemed appropriate for sand dams.

To our knowledge, no prior study has suggested bottom-aperture outlets to achieve optimal sediment accumulation. Field implementation could follow a two-step process: the dam would initially be constructed with a bottom outlet. This outlet would later be closed once approximately 70%–80% of the reservoir is filled with sand. This approach may be more practical than staged vertical-lift construction, currently regarded as best practice for minimizing silt and clay accumulation. While a two-stage top-notch dam may be comparable in cost and effort, bottom openings appear particularly effective at managing silt and clay, offering a potentially superior alternative for sediment control. To ensure structural integrity when implementing a bottom-aperture outlet, the outlet foundation could be reinforced with rebar placed incrementally in parallel to the base, effectively coupling it with the surrounding structure. Maintaining a stronger top section of the dam can further help resist erosion and protect the structure from downstream scouring. These reinforcement strategies provide practical guidance for safe construction and long-term durability of sand dams with bottom outlets.

In addition to optimizing the gradation of collected sediment to facilitate water storage and abstraction, this research may also be applied to sand collection systems. Globally, there is high demand for coarse sand for use in construction. Small bottom-outlet reservoirs might be built on streams near where sand is needed, providing a self-replenishing source of construction sand. In locations where riverbed sand is mined for construction use, it may be useful to design structures that effectively and selectively trap particles based on their size. More broadly, the principles demonstrated here—controlling sediment deposition through outlet geometry—could be applied to other small-scale water retention and sediment management structures, such as check dams, infiltration basins, or restoration projects, across diverse geographic and hydrological settings.

However, the practical implementation of outlet-based designs in sand dams presents challenges beyond hydrological considerations. Many community-led sand dam projects rely on donor funding and non-profit implementation, where demonstrating immediate water storage benefits is a priority. There may be significant resistance to constructing a dam with a bottom outlet, especially in areas where sand dams are not yet common, as communities may be unfamiliar with the long-term benefits of water flow control. In contrast, in areas where siltation is a recurring issue, the community may be more receptive to these designs. Successful implementation of this approach would require addressing these community concerns, potentially through education and sensitization, particularly in regions without previous experience with dam construction. Future research should explore strategies to balance technical effectiveness with community acceptance, potentially integrating staged or adjustable outlet designs that allow for adaptation over time.

4.2 | Sediment Retention and Hydraulic Impacts of Bottom Outlets

A key consideration is to ensure that the outlet does not negatively impact the dam's function during larger, overtopping events. In such cases, pressure flow through the outlet could alter local hydraulic conditions, potentially affecting sediment retention. However, our results show that during higher flow events at 11 m^3/s where flow reaches the edge of the overtop, the Rouse number—a key indicator of sediment suspension—does not appear to vary significantly with the outlet design. Coarser particles larger than ~1 mm continue to be retained within the reservoir and deposit upstream of the dam, with the bottom outlet not introducing negative effects on sediment retention during large flows. Future work should still explore the influence of pressure flow on sediment dynamics to further confirm these findings.

While the ET-shaped outlet is designed to be effective during low to moderate flows, it is important to acknowledge that it may not be large enough to convey larger flows associated with overtopping events. The outlet's design does not aim to manage high discharge flows, which would exceed the outlet's capacity. In the event of flows exceeding the outlet's capacity, provisions for passing larger flows should be considered. For example, overflow spillways or reinforced weir sections could help convey excess discharge, particularly in channels where erodible banks or asymmetrical geomorphology may alter the flow path.

Furthermore, while fine sediment remains in suspension with bottom outlets during low flows, it is essential to ensure that it does not reduce the dam's capacity to trap and retain coarse-grained sand, which is the primary goal of sand dams as a water storage mechanism. Our results suggest that coarse sediment transport occurs primarily during higher flow events, when the outlet's influence is minimal. Nonetheless, these conclusions are based on numerical modeling, and real-world variability in sediment supply and hydrology may produce different results. Field validation will be essential to confirm whether bottom-outlet structures function as effectively under natural flow regimes and heterogeneous sediment inputs. Pilot-scale implementations could provide valuable evidence on their long-term reliability and maintenance requirements.

4.3 | Limitations and Further Studies

Our methods included several assumptions. While the Rouse number method is commonly used to evaluate sediment suspension, it primarily relies on shear velocity, which is often derived from bed shear stress (Ralston and Stacey 2006). However, shear velocity can be more generally defined based on shear stress at any point in the flow, not just at the bed. This approach assumes that bed shear stress is the dominant driver of sediment suspension, though vertical turbulence also plays a role. However, though it is reductive, the Rouse number method provides a practical and useful way to predict sediment suspension dynamics and is precedented in relevant literature (Pekker 2017; Richardson and Davis 2001; Van Rijn 1993; Whipple et al. 1998). Additionally, the effects of sediment deposition and delta progradation were ignored, and one-dimensional modeling in HEC-RAS assumed that shear stress is uniform across cross-sections. In addressing these limitations, we draw insights from our ongoing experiments. Preliminary findings suggest that the transport and deposition of bedload result in streamwise delta progradation, gradually filling the reservoir primarily with deltaic sediment. Sand dams equipped with ET aperture are anticipated to accumulate multiple deltas, each corresponding to different storm events, stacked on top of each other in their deposits. These stacked deposits reflect the episodic nature of sediment delivery. Experiments to be discussed in follow-on publications have shown the formation of a flat-topped delta near the upstream end of the model reservoir, with progradation downstream throughout the experiment as bedload sediments were deposited on the delta's slope face (Kleinhans 2005).

Another area for future research involves understanding the impact of downstream conditions on the effectiveness of outlet structures. While conventional sand dams are relatively insensitive to downstream conditions due to the drop over the dam wall, in the case of our proposed design, backwater effects from downstream obstructions could propagate upstream and limit the effectiveness of the outlet. These effects could reduce flow through the structure, particularly during low flows when backwater influences become more pronounced. Investigating these hydraulic interactions will be important to ensure that the outlet design performs consistently across a variety of flow conditions. Additionally, the rehabilitation of existing, poorly performing sand dams with openings at the bottom could provide a practical, low-risk opportunity to test whether subsequent floods and sediment deposition gradually replace fine layers with coarser material, thereby improving storage performance over time.

These findings underscore the need for future research, which will specifically address sediment behavior with different outlets. The authors plan to conduct physical experiments and three-dimensional numerical modeling to evaluate how the study's assumptions hold up under more realistic conditions. Overall, these results should be viewed as a first step, providing theoretical and numerical justification for outlet-based designs. The next phase, physical experiments followed by field trials, will be critical in testing the robustness of these assumptions in complex, real-world settings.

5 | Conclusions

In this study, the particle Rouse number was used to assess which particles would accumulate within sand dam reservoirs under various low flow rates and with outlets of varied geometries. If other formulations for sediment transport are preferred over the Rouse number, the same optimization strategy could be used to obtain outlet structures consistent with these alternative geomorphic predictors. To maintain favorably high values of porosity and specific yield and to minimize the capillary fringe height, we sought to identify an outlet configuration that would discharge all particles smaller than 0.125 mm and trap coarser material. This approach can be adapted for other particle sizes, as the terms "fine" and "coarse" are relative and depend on the specific sediment transport dynamics and local conditions at each site.

We suggest that constructing the dam with ET or PET-shaped outlets could achieve this deposition across a broader range of flow rates than those tested in this study, which covered 1.0–11 m^3/s and may not represent the full spectrum encountered in typical sand dam applications. The ET-shaped outlet, with its wider base and narrower top, enhances sediment management by improving sediment transport efficiency and minimizing fine particle deposition. The wider base allows higher flow velocities near the reservoir floor, reducing fine sediment accumulation, while the narrowing of the outlet slows the flow, facilitating the deposition of coarser particles and keeping fine particles suspended. Outlets at the bottom with simpler geometries such as triangular or square openings also performed well and are easier to construct.

The ET-shaped outlet was confirmed to achieve the target Rouse number using HEC-RAS simulations. Other findings include the following:

1. At low flow rates, both the ET-shaped outlet and other outlets at the bottom would prevent the deposition of particles smaller than 0.125 mm, with the ET-shaped outlet slightly outperforming the other shapes by maintaining a more consistent Rouse number across the tested range of flows.
2. Typical top-notch outlets do not achieve desirable depositional conditions at low flow rates.
3. A more practical version of the Eiffel Tower shape, with straight edges and a narrower bottom, provides similar performance to the true ET shape. This is essential in real-world applications to facilitate construction and avoid structural issues.
4. In practice, the bottom-notch and bottom-square shapes may be preferred for ease of construction.

This study presents modeling results suggesting that management of reservoir sedimentation is possible by installing dams with strategically shaped outlets. The combined approach of using HEC-RAS modeling and mathematical calculations highlights a promising method for designing outlet structures in sand dams, optimizing for sediment transport and reservoir efficiency. Importantly, as discussed above, bottom-aperture outlets could be implemented through a two-step process: constructing the dam with a bottom outlet that is later closed once the reservoir is largely filled with sand. This approach offers a more practical and effective alternative to staged vertical-lift construction currently used to minimize siltation.

After further assessment of this approach through physical modeling and three-dimensional numerical modeling, we hope to disseminate our results and recommendations to non-governmental organizations and governments involved in sand dam construction. It is our hope that this approach will eventually be applied in the field to improve the performance of sand dams built for water supply.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that supports the findings of this study are available in the Supporting Information of this article.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** Supporting Information. **Data S2:** Supporting Information. **Data S3:** Supporting Information. **Data S4:** Supporting Information.