SEDIMENTATION PROCESSES: GEOMORPHOLOGICAL EVIDENCE FOR STAGED SAND DAM CONSTRUCTION

ABSTRACT

Steam sediment transport is a convolution of climate, weather, geology, topography, biology, and human influence. In addition to providing water and food security for dryland rural communities, sand dams—small weirs designed to trap only the coarse fractions of transported sediments in seasonal and ephemeral streams—illuminate many complexities of geomorphological dynamics. Sand dams store water in interstitial riverbed pores and the size of deposited sediment particles largely determines the recoverability of stored water: fine materials limit transmission and provide lower volumetric yield. Can a sand dam be designed for a particular reach-scale, hydro-sedimentary context to limit capture of fine particles? We argue that the Rouse number provides a useful criterion for identifying regimes where the target material grades are trapped. These ideas were tested using sediment data collected in Kenya and HEC-RAS numerical simulations to evaluate the sensitivity of sedimentation processes to spillway height. We show that constructing sand dams in stages results in more targeted trapping of coarse material. Surprisingly, sedimentation is shown to be more sensitive to variation in spillway height than the flood hydrograph, especially when a dam is short. A method for evaluating the need for spillway staging (essentially controlling the bedform) based on the modeled Rouse number allows evaluation of costs and expected benefits. Beyond sand dams, this supports the observation that for dryland streams with peaky flows and high sediment loading, local hydraulic controls are typically more diagnostic of streambed sediment composition than is the sediment source.

Keywords: Sand dam, Rouse number, sediment transport, bedload, Kenya, sand, spillway, semi-arid

INTRODUCTION

Rural communities located throughout the world's drylands frequently collect and store surface water during wet periods for use during dry periods (Lasage, Aerts, Mutiso, & de Vries, 2008; Nilsson, 1988; Wipplinger, 1953). The hydromorphology of streams in these regions is often closely linked to water security and provides a nexus for sedimentology, hydrology, and water supply. Open-water reservoirs in arid and semi-arid regions face challenges of evaporation and siltation that can drastically reduce effective storage capacity and dam efficiency (Quilis et al., 2008; Wipplinger, 1953). Additionally, open water is more susceptible to contamination by livestock, is more likely to host disease and disease-carrying vectors, and presents a drowning hazard.

Sand dams provide an alternative to surface reservoirs. Sand dams are reinforced concrete or stonemasonry weirs constructed across ephemeral or intermittent, sand-bedded streams underlain by a stable, low-permeability layer. Rather than filling with clay and silt, well-designed sand dams primarily trap coarser sands and gravels. By blocking subsurface flow and increasing the riverbed volume upstream of the structure (Fig. 1), sand dams produce and enhance interstitial water storage.

Many sand dams store tens of thousands of cubic meters of water (Quilis et al., 2008) and create permanent or semi-permanent shallow aquifers in the riverbed, providing dry-season water for people, animals, and small-scale agriculture. Water is typically abstracted using traditional, hand-dug scoop holes or higher-cost, protected sources (Hussey, 1997; Nilsson, 1988).

SAND DAMS AND SEDIMENT TRANSPORT

Sand dams are typically constructed in regions with sporadic, intense, and erosive precipitation (Edwards, Classen, & Schroten, 1983; Mansell & Hussey 2005) and soils with low infiltration rates (Reid & Frostick, 1987; Rodier, 1990). Together these characteristics produce a rapid onset of overland flow in response to rain events. Flows in ephemeral and seasonal streams are generally flashy with very high sediment transport rates. Most sediment travels as suspended load during storm flows, especially during the rising limb and early in the runoff season when supply is essentially unlimited (Alexandrov, Laronne, & Reid, 2003; Negev, 1969). Powell, Reid, Laronne, & Frostick (1996) show that suspended sediment frequently comprises more than 90 percent of the total sediment load for dryland ephemeral rivers.

Like other surface-water dams, a newly constructed sand dam produces a backwater with increasing cross-sectional area, decreasing velocity, and decreasing turbulence in the direction of flow. Reduction in turbulence allows coarse sediment to drop from suspension, forming a delta at the upstream end of the backwater (Fig. 2). Smaller, lighter particles are either deposited closer to the dam wall, forming a wedge-shaped bottomset bed, or remain in suspension and flow over the top of the structure. The coarse delta migrates downstream until it reaches the dam wall, filling the reservoir to the level of the spillway over one to several rainy seasons.

The size of sediment particles trapped by a sand dam dramatically affects the structure’s ability to store, transmit, and yield water. Well-graded and coarse sediments exhibit ideal hydraulic properties due to their high porosities, permeabilities, and specific yields. Fine sediments (silts and clays) have much lower permeabilities and specific yields, negatively affecting sand dam performance (Hofkes & Visscher, 1986; Nilsson, 1988). Fine sediments also exhibit more capillary rise and greater evaporative losses, and often support phreatophytic plants resulting in transpiration losses (Hellwig, 1973).

All sand dams trap some silt- and clay-sized sediment. Localized deposits of fines are common within a generally coarser bed, especially when a dam requires many storms to fill (Borst & de Haas 2006). Fine sediment near the surface of the riverbed is often eroded due to management practices or wind during the dry season (Borst & de Haas, 2006) or remobilized and replaced with coarser particles during subsequent flow events (Gijsbertsen, 2007; Wipplinger, 1953). However, the competence of flows to mobilize silt and clay from thick bottomset beds, while often assumed, is not well documented. In many cases, the bottomset bed is simply buried by the coarser delta, reducing the structure's storage capacity (Viducich, 2015).

Approximately half of all sand dams suffer from significant storage problems due to the deposition of fine sediment, though definitions of success and numbers reported by researchers and practitioners vary widely (De Trincheria, Wibbing, Leal Filho, & Otterpohl, 2016; The Water Channel, 2010; Viducich, 2015). For this study, we define a successful sand dam solely in terms of its sedimentation profile: a successful sand dam releases water from its entire aquifer depth under gravity. We propose that a median particle size of 0.5 millimeters (mm) is likely acceptable for most sites, acknowledging the roles of grading and aquifer depth in drainage. Coarser sediment is more important for drainage in shallow aquifers, due to the lower (negative) pore pressures (Viducich, 2015).

Sand dam spillway design

Myriad factors affect the size of sediment particles trapped by a dam, but the height of the spillway is one that may be easily controlled. Many sand dam practitioners and design manuals advocate staged spillway construction to maintain the forces required to keep fine sediment particles in suspension. In staged construction, a dam's spillway is initially constructed to a fraction of its final height to maintain greater upstream velocities and turbulence and discharge fine sediment; predominately coarse particles are trapped. A second stage is added after trapped sediment fills the dam to the level of the first stage, and the process is repeated until the final spillway height is achieved.

Many practitioners recommend the use of a standard stage height for every dam, regardless of a site's characteristics. Standard stage heights are easily implemented but suggested values vary substantially (Diettrich, 2005; Hofkes & Visscher, 1986; Maddrell & Neal, 2012; Nissen-Petersen, 2006; Nissen-Petersen, 2011; RAIN Foundation, 2008). A standard stage height appropriate for every sand dam must be overly conservative for most sites, incurring extra costs. Other researchers and practitioners identify a need for site-specific approaches to spillway design (Borst & de Haas, 2006; De Trincheria et al., 2016; The National Academy of Sciences, 1974; Gijsbertsen, 2007; Wipplinger, 1953). Notably, Wipplinger (1953) proposes a staging design principle based on local hydraulic controls, suggesting that sand storage dams should be designed to maintain a velocity of at least 0.46 meters per second (m/s) "a short distance upstream of the dam wall" to prevent deposition of fine sediment.

Despite the common recommendation to build sand dams in stages, the technique is only rarely employed due to the uncertain methods and benefits, the additional transport and construction costs (Kyalo, 2015; Maddrell & Neal, 2012), social constraints, and limitations imposed by project funding cycles (Munguti, 2014). We attempt to address the first set of challenges—uncertain methods and benefits—by proposing a new method for assessing the site-specific need for spillway staging based on local hydraulic controls. Rather than attempting to explicitly model sediment transport, our method envisions a sand dam as a low-pass filter designed to pass particles finer than a given size. The method employs data that may be readily collected in the field. Software (HEC-RAS) is available free of charge from the United States Army Corps of Engineers Hydrologic Engineering Center (www.hec.usace.army.mil/software/hec-ras/).

DATA COLLECTION AND ANALYSIS

Study area

Field work was conducted in Kitui and Makueni Counties, Kenya, in partnership with three groups who together have constructed more than 1,000 sand dams: Sahelian Solutions (SASOL), the African Sand Dam Foundation (ASDF), and ASAL Consultants (ASALCON). The counties receive rainfall during two annual, increasingly-variable rainy seasons known as the "long rains" (approximately March through May) and the "short rains" (roughly October through December). Most sites receive just a few storms, on average, during each rainy season, typically falling within a period of a few weeks. Droughts are also relatively common, occurring roughly every 4 to 5 years (Lasage et al., 2008).

Data were collected at 11 sand dam sites (Fig. 3) representing a range of sedimentation results, including several dams that filled with fine sediment and do not perform well. To honor our partners' willingness to highlight both successful and unsuccessful sites, each dam was randomly assigned a numeric identifier.

Data collection

Flow characterization measurements were taken a short distance downstream of each dam on a straight reach where uniform flow could be reasonably assumed. Cross-section survey data, high water marks, crowd-sourced information, and Manning's equation were used to develop flow hydrographs for the first storm events following each dam's construction (Viducich, 2015). The use of crowd-sourced data for flow characterization is not without precedent—Nilsson (1988) describes the use of terrain marks and interviews for determining peak flows, and the method is frequently used in sand dam design. Given the paucity of gaged rainfall and flow data throughout much of sub-Saharan Africa, crowd-sourced data provide otherwise-unavailable information.

Soil core samples were collected 10, 50, 100 and 150m upstream of each dam and partitioned into samples representing approximately 50-cm depth intervals. The samples were dried, weighed, chemically dispersed, and the fine fraction was characterized using the hydrometer method as described by Gee & Bauder (1986). Each sample was then wet sieved, dried, and dry sieved to characterize the coarser fraction.

We developed bulk particle size distribution curves for each site and computed four additional sediment parameters to facilitate comparison (Table 1). Three are based on the D_{50}, or the diameter for which 50 percent of the sample is finer by mass: 1) the bulk median particle size at all locations, 2) the D_{50} for all samples taken at the 10 m location alone, and 3) the D_{50} for samples collected at all locations other than those at 10 m. The fourth parameter is the average Hazen's Uniformity Coefficient (C_U), or D_{60}/D_{10}, of each site's samples to quantify the sediment grading. Over half the sites have sediment coarser than the suggested 0.5 mm median particle size threshold. Some sites have similar D_{50} values but different uniformity coefficients, suggesting differing hydraulic properties. A comparison of each site's three D_{50} values illuminates fining at the 10 m location for some dams, corresponding to the presence of a thick bottomset bed.

Hydraulic modeling

We developed one-dimensional HEC-RAS 5.0 (Beta 2014-10-01) hydraulic flow models using field data to test the role of local hydraulic controls in sedimentation processes and to evaluate the predicted sensitivity of sediment trapping dynamics to spillway height. Three sites (2, 8, and 9) were selected for hydraulic modeling based on the completeness of their flow and sediment datasets, variation in their sedimentation profiles, and their relatively simple channel geometries. All three dams were built in a single stage to final spillway heights of 1.05, 1.9, and 1.7 m, respectively.

A cross section surveyed 50 m downstream of each dam was used to develop the model geometry, with the assumption that any downstream channel degradation was reversed after the dam filled with sediment and supply was restored. The cross section was extrapolated upstream over the full length of the backwater using the original channel slope (0.005 to 0.006) as recorded by the practitioner and verified on site. Manning's *n* values for the riverbed and banks were estimated based on channel characteristics; most sandy riverbeds were assigned Manning's *n* values of 0.025, while bank values ranged from 0.03 to 0.06 (Chow, 1959). An inline weir structure was modeled at the dam location using dimensions measured in the field. We developed four separate dam geometries for each site: no dam, and dams with spillways 1⁄3, 2⁄3, and the full constructed height.

We prepared unsteady hydrographs for each site using a modified surge function (Voytenko, 2011) to match the reported flows. Two additional, modified hydrographs were also developed for each site—one with increased duration (50%) and one with increased magnitude (10%) of the peak flow—to evaluate the sensitivity of sedimentation processes to hydrograph changes relative to changes in the spillway height.

We selected the Rouse number (Equation 1) to compare the effects of varying channel and dam geometries and discharges on sediment transport. The Rouse number is the ratio of a particle's settling velocity, ω_0, to the product of the von Kármán constant, κ, and the shear velocity, u_*. The parameter compares the relative effects of forces acting on a sediment grain of a given size in the vertical directions and provides a rough indication of the mode of transport. While proposed ranges vary by source (Dade & Friend, 1998; Julien, 2010; Van Rijn, 1993), Table 2 provides typical values assumed for the current study.

$$Rouse ¿ = \frac{\omega_o}{\kappa u_¿} Rouse\ \# = \frac{\omega_0}{\kappa u_*} Rouse\ \# = \frac{\omega_0}{\kappa u_*} \quad (1)$$

We computed the Rouse number as a function of time and distance upstream of each dam for 0.008 mm, 0.125 mm, 0.5 mm, and 1 mm particles (representative of fine silt, fine sand, coarse sand, and very coarse sand size classes, respectively (Vanoni, 2006)). In our model, particles transported as bed load were assumed to be trapped by the dam, while particles that approached the structure in suspension were discharged; a Rouse number of 2.5 represented the threshold value indicating particle fate. We also assumed the trapping process described by the Rouse number is the primary mechanism determining the composition of the sediment bed. Other processes, like settling of suspended sediment after flow has ceased or scour of deposited sediment by subsequent storms or non-fluvial forces, play minor roles in determining the bulk sediment characteristics throughout the dam's storage volume.

Predictably, modeled Rouse numbers varied with time (reflecting unsteady flows) and location. Large discharges at the beginning of a storm hydrograph produced large shear stresses and velocities, increasing the tendency for a particle to travel in suspension. Likelihood of trapping increased as particles approached the structure and shear velocities decreased. For each flow case, we calculated the fraction of the total flow period during which particles of the four representative sizes were expected to travel in suspension at a location 1/20th of the dam's total backwater length (210 to 425 m) upstream of the structure. Fig. 4 presents the modeled time percentages for the nominal case with the full spillway height and reported hydrograph. Fine particles were most often discharged at Site 2, followed by Sites 9 and 8, suggesting the same ranking order for the predicted D_{50} particle sizes from coarsest to finest.

These results align with sampled distributions for the three sites (Fig. 5), providing some validation. It is difficult to interpret the spread of the particle size distributions, but the sites' uniformity follows the same order as the median particle size due to the larger Hazen's Uniformity Coefficient (C_U), or D_{60}/D_{10}, values associated with finer samples (reflecting samples from the bottomset bed).

We used Equation 2 to evaluate relative sensitivity of sedimentation dynamics to modeled variations in three parameters: spillway height, discharge magnitude, and duration of peak flow. For each parameter, relative sensitivity was calculated using the modeled time-percentage results for a 0.125 mm (fine sand) particle as the response variable, for both the nominal and altered cases. The full spillway height and reported hydrograph for each site represented the nominal case, while the parameter variation and associated response represented the altered case. Fine sand was selected because it was both discharged and trapped for some portion of the total modeled flow time for all sites and it may represent a theoretical minimum acceptable particle size.

$$Relative\,sensitivity = \frac{\dfrac{Response_{altered} - Response_{Nominal}}{Response_{Nominal}}}{\dfrac{Parameter_{Altered} - Parameter_{Nominal}}{Parameter_{Nominal}}} \quad (2)$$

As expected, shorter spillways increased the likelihood that a fine sand particle would travel in suspension throughout the backwater (Fig. 6). Modeled results indicate that for Site 2, the 1/3 spillway height case limits deposition of fine sand to the reach stretching approximately 50 m upstream from the dam, and only during the receding limb of the storm hydrograph.

For all three sites, modeled sedimentation processes associated with 0.125 mm particles are substantially more sensitive to variations in spillway height than to variations in the magnitude of discharge or duration of the peak flow over the modeled ranges (Table 3). The relative sensitivity of sedimentation processes to spillway height is greater at lower heights, with sensitivity varying across sites.

CONCLUSION

This study supports the field observation that it is possible to design hydraulic structures for sediment transport in some dryland streams without deep knowledge of climate, sediment supply, and other complex factors. Staged spillway construction results in the selective trapping of coarse material, which would be expected to reduce the failure rate of sand dams due to siltation. Of all the results from this research, perhaps most striking is the observed weakness of the relationship between constructed spillway height and the median size of trapped sediment for the study sites. Therefore, we conclude that a standard spillway stage height is not appropriate for all dams. The relative benefit of spillway height staging is shown to be site-specific, and many sites—including over half of those studied—did not require staging to yield acceptable results. Given the potentially high costs required to produce limited additional benefits in these cases, the universal application of staged designs is neither necessary nor appropriate.

We propose that numerical hydraulic modeling of local, dynamic flow conditions using the described methods may be useful for practitioners in determining whether and how to stage a given sand dam's spillway. When spillway staging is deemed necessary, smaller stage heights should be used for sites more likely to trap fine sediment. Also, based on the results of sensitivity analysis, strategic spillway design may lend itself to smaller initial stages and increasingly taller stages as a dam is raised.

These observations could be seen as natural conclusions from the work of Gilbert (1877), who wrote "…the velocity determines the size-limit of the detritus that a stream can move…" While this language is imprecise—velocity is an important factor in drag and turbulent forces but itself is not a force capable of lifting or transporting sediment—Gilbert correctly observes the importance of local hydraulic controls in determining the fate of transported material. While Gilbert viewed this as a feature of nature, here we invert the principle as a basis for design. Flow velocity and related forces can be predictably controlled without extensive knowledge of the watershed or climate in which a structure is built, allowing for fully general design of some critical hydrogeomorphic systems.

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TABLES

Table 1. Characteristic Bulk Sediment Parameters for the 11 Dam Sites.

Site	**Height (m)**	**D_{50} - All (mm)**	**D_{50} - No 10 m (mm)**	**D_{50} - 10 m (mm)**	**Hazen's C_U**
1	1.51	0.643	0.632	0.665	5.77
2	1.05	0.653	0.671	0.618	3.62
3	1.25	0.428	0.523	0.205	4.04
4	1.19	0.529	0.534	0.525	8.72
5	2.3	0.516	0.643	0.177	20.28
6	1.37	0.184	0.287	0.116	96.63
7	1.94	0.612	0.560	0.569	11.17
8	1.9	0.433	0.435	0.428	9.74
9	1.7	0.513	0.588	0.289	9.18
10	2.25	0.384	0.408	0.334	7.10
11	2.22	0.219	0.225	0.200	13.03

Table 2. Rouse Number and Mode of Transport.

Rouse #	Mode of transport
0 - 0.8	Wash load
0.8 - 2.5	Suspended load
2.5 - 7.5	Bed load
> 7.5	At rest

Table 3. Relative Sensitivity of Modeled Sediment Response to Varied Spillway Height and Flow Parameters.

Model Parameters		**Site 2**		**Site 8**		**Site 9**	
Parameter	*Range*	*Response*	*Rel. Sens.*	*Response*	*Rel. Sens.*	*Response*	*Rel. Sens.*
Nominal	0.0%	26.7%	-	4.3%	-	6.1%	-
Spillway height	-33.3%	39.6%	-1.4	6.0%	-1.1	8.2%	-1
Spillway height	-66.6%	64.4%	-2.1	11.2%	-2.4	32.3%	-6.4
Discharge magnitude	+10.0%	28.7%	0.7	4.5%	0.3	6.5%	0.7
Peak flow period	+50.0%	28.8%	0.2	4.9%	0.3	6.5%	0.1

FIGURE LEGENDS

Fig. 1. Cutaway View of a Mature Sand Dam.

Fig. 2. Typical Sand Dam Early in the Sedimentation Process.

Fig. 3. Study Sites in Kitui and Makueni Counties, Kenya.

Fig. 4. Fraction of Total Modeled Flow Time Particles Were Discharged by Dam for the Nominal Case (Full Spillway Height and Reported Hydrograph).

Fig. 5. Bulk Particle Size Distributions of Sampled Sediment. Site 2 Sediment is Coarsest and Most Uniform.

Fig. 6. Rouse Number Surface Plots for Full (A) and 1/3 Spillway Height (B) Cases