Movement of pebbles on a sand bed river, Botswana

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Abstract Movement of magnetically tagged pebbles was examined on an ephemeral sand bed river in Botswana. In addition, scour and surveyed cross-sections were analysed. After the first flood season, the tagged pebbles were dispersed over a 2 km long reach. The distance of movement varied substantially between particles and between flow events, and was related to burial depth and channel morphology. The distance of movement decreased with increased burial depth. Most of the tagged pebbles were deposited in bars, from which a low percentage were released in the succeeding event. The recovery rate, about 25%, was low due to most of the particles becoming deeply buried, greater than one metre, within the sand. After the first flood season, most of the deeply buried stones remained stationary during subsequent floods. However, due to aggradation and degradation their depth, relative to the local bed surface, changed. The mean burial depth of the tagged pebbles decreased with downstream distance. A similar pattern was obtained for the scour and fill data. The mean burial depth was intermediate between the mean depths of scour and fill. No trend was found in the particle depth distribution over time.

INTRODUCTION

Rivers are often classified, among other things, based on the sediment texture of their bed. Generally, sand rivers are defined as low gradient rivers with beds composed mainly of sand particles. While the median particle size and the bulk of the bed material of a sand bed stream falls in the sand size range, a small proportion of gravel, silt or clay is usually present. Sand bed rivers are common in arid and semiarid regions, and have a widespread distribution in the southern African sub-continent.

Much of the human settlement is concentrated around these rivers. In Botswana, about 30% of the rural population extract their water supplies from wells dug into the beds of sand rivers (Shaw et al., 1994). In addition, rivers are an important source of sand for building and other uses. Since 1974, for example, about 100 000 m³ year⁻¹ of
sand have been removed from the Motloutse River for smelting flux (Shaw et al., 1994).

While an important source of water and materials, sand rivers are also a sink for human waste. In the case of Botswana, increasing levels of pollution have been noted. Contaminants enter the water flow and settle in the active layer of the river bed. Ultimately, some of these contaminants reach the water table and pollute it.

Despite their importance as a resource, knowledge of the movement of gravels in sand bed rivers is poor. Field observations are limited to a few sites. In this paper we examine the three-dimensional dispersion of tagged gravels in sand bed rivers.

The Metsemotlhaba project

The Metsemotlhaba River is a tributary of the Notwane River, itself a tributary of the Limpopo River. The Metsemotlhaba River drains a 615 km$^2$ elongated catchment. The study reach is located between the villages Moshupa and Thamaga (Fig. 1). At this point, the study reach is 1500 m long and 20 to 40 m wide. The reach consists of point bars, mid-channel islands, and relatively flat areas. The river bed at the project site has a fairly consistent and symmetric sand size distribution, both in surface and subsurface samples, with a median grain size of about 0.4 mm. In addition, small pebbles are scattered on the bed surface and within the active layer. The sand deposits occur as a continuous layer over a series of basins in the channel substrata.

Flow is ephemeral by nature, flooding in response to precipitation events within the

![Fig. 1 Location map: the upper Metsemotlhaba catchment.](image)
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catchment. In addition, flows are highly unsteady and short with an average of three to five events per year. The hydrograph of a flow event has the characteristic steep rising limb of a flash flood and a long falling limb. Peak discharges range between an annual peak discharge of $110 \text{ m}^3 \text{s}^{-1}$, and a low peak of $8 \text{ m}^3 \text{s}^{-1}$.

METHODS

Data collection focused on both hydrological and sediment monitoring. Magnetically tagged particles were used to simulate the movement of individual stones (Hassan et al., 1984). A total of 865 particles were injected in six lines, of which 710 were small synthetic magnetized stones weighing 15 g each. The remaining particles were large natural pebbles ranging between 32 and 90 mm in size.

Scour chains were installed in six sections along the study reach. Each section included about 10 chains located across the channel. A total of 60 chains were installed. In addition, 15 cross sections covering a longitudinal distance of 1400 m were surveyed. The periodic resurvey of these sections provided the information on bulk changes over time.

RESULTS

Movement of tagged particles

Seven flow events were recorded during the 1987-1988 rainy season. The first event, after the placement of the tagged particles, was the largest recorded event over the study period. All of the recovered particles were found buried and the resulting spatial distribution for the season is illustrated in Fig. 2. The Figure shows that most of the particles were found in groups, while some were scattered throughout the study reach. In addition, a high proportion of the tagged particles were found near the island (stations 1150-1250) and in the associated downstream point bar (stations 1300-1500). The events which occurred during the 1988-1989 and 1989-1990 flood seasons were relatively small and many particles did not move. Therefore, the location of the tagged particles did not change significantly.

Figure 3 shows the location of the moved particles before and after the 1991 flood season. Many of the moved particles were placed on the bed surface before the 1989 flow events. Generally, the figure shows that areas which contribute gravels were also the preferable areas for sedimentation. In summary, the spatial distribution of the tagged particles was dominated by the first event which was the largest recorded event over the study period.

The relation between distance of movement and particle size was examined after flow events. The distance of movement varied between particles and between seasons with no relation between distance of displacement and particle size (Fig. 4(a)). These results concur with those of Leopold et al. (1966); Schick et al. (1987); Hassan & Church (1992) and other field and flume studies.

The mean distance of movement and burial depth after the December 1987 event, the first and the largest recorded event after the injection of the tagged particles, were 842 m and 44 cm, respectively. The March 1991 flood was approximately of the same
Fig. 2 Distribution of tagged particles recovered after the 1987-1988 flood season. Distances along the reach are in metres.

Fig. 3 Tagged particle movement between 1989-1990 and 1990-1991 flood season. Original (pluses) and final (circles) positions are shown. Distances along the reach are in metres.
magnitude as the December 1987 event, however the mean distance of movement was 310 m only. It seems that the shorter distances of movement by the March 1991 event are due to the fact that most of the particles started from buried positions, rather than from initial surface positions which characterized the December 1987 event.

The relation between depth of burial and particle size was examined. Figure 4(b) demonstrates the lack of relation between burial depth and particle size. In addition, the Figure shows that some particles were deeply buried while others of the same size were found close to the bed surface. These observations are similar to those obtained from gravel bed rivers (e.g., Hassan & Church, 1994). However, in sand bed rivers, burial depth is dominated by the movement of bed forms, while in gravel bed rivers the scour and fill, and the movement, are local and sporadic.

The distance of movement was found to vary with burial depth. Particles located on or close to the bed surface by the beginning of a flow were found to move, on average,
larger distances than deeply buried particles. In addition, the mean burial depth decreased with downstream distance. A downstream reduction in the burial depth of sand grains was observed in a flume experiment by Crickmore & Lean (1962a, b).

Estimation of sediment transport

Volumes of bed load transport were calculated using the mean distance of movement of the tagged particles, the mean depth of the active layer based on both scour chains and burial depth of tagged particles, and the mean width of the study reach. The estimated volume for the largest recorded events during the study period were 18 300 m$^3$ and 5800 m$^3$ for the December 1987 and the March 1991 events, respectively. On the other hand, small events yielded 420 m$^3$ (1988-1989), 90 m$^3$ (1989-1990) and almost zero (1991-1992).

SUMMARY

The paper has examined relations between travel distances and burial depth of tagged gravels on sand bed rivers, and sediment characteristics and flow conditions. The study confirms the lack of a simple relation between distance of movement and particle size. Also, grain size was found to have no influence on burial depth of particles.

On the local level, it became clear that bed load transport by high magnitude floods in Botswana exceeded by far previously assumed values. The system is a dynamic one, which erodes at an appreciable rate the available sand volume, a non-renewable resource of prime importance to the Botswana livestock industry.

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