International Journal of the Physical Sciences Vol. 5(6), pp. 1227-1230, 4 August 2010
Available online at http://www.academicjournals.org/IJPS
ISSN 1992 - 1950 ©2010 Academic Journals

Full Length Research Paper

Sand water storage systems using coefficient of uniformity as surrogate for optimal design : A laboratory study

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Accepted 5 July, 2010

Uneven surfaces of sand particles provide ideal opportunities, under arid conditions, for runoff to be stored in the voids of sandy riverbed of ephemeral river. Series of laboratory experiments were performed to study major controlling parameters of sedimentation in sand water storage in order to optimize storage potential. Analysis was based on coefficient of uniformity of grain size distributions of deposited sediments. Ideally, desirable sediment grade for optimal water storage in sand reservoir is uniform sand grade with coefficient of uniformity less than 5. The results can be used to determine height of weir given required grade of sand and the flow conditions.

Key words: Floodwater harvesting, sedimentation, sand river, groundwater storages

INTRODUCTION

Water scarcity is a limiting factor to human settlement in rural areas of South Africa where water delivery is difficult due to arid conditions. Ephemeral Rivers are prominent groundwater sources in the remote communities. Ephemeral River is a seasonal river from which water flows periodically and for short periods following heavy rain. Flowing surface water in ephemeral rivers is usually of little direct use to people because of the short duration of flow. Important quality of ephemeral river is that, there is usually a significant volume of water beneath the riverbed despite surface remains dry. This is evidence by luxuriant vegetations growth along the river banks. Seasonal flood flow transports sediments (sand and gravel) downstream and saturates the sand deposits that form the riverbeds.

Sand water reservoirs are mainly built in ephemeral rivers to trap sediments and groundwater flow. The sand water reservoirs are built by obstructing sediment laden flow using weir and allowing sediments deposition thus forming artificial aquifer. Sand water storages have the advantages of being able to store large volumes of water than the natural aquifers and of being less susceptible to evaporative losses as the water is stored underground (UNEP, 1997). The sand riverbed is used as a natural filter and has negligible turbidity (Clanahan, 1997). Water stored is suitable for drinking, as well useful for irrigation purposes during prolonged dry periods. Stored water can be abstracted by gravity pipeline, if topographical conditions are favourable or by tube well.

Water from sand reservoir is characterised by low yield and often considered unpredictable. The reasons to that are clogging of river bed by fine sand particles and underground seepage. The later is solved by sitting on impermeable layers. While variations in size of sand grains and different rates of sand grains transport during flow can be used to advantage in former. Traditionally, in sand water storage, construction of weir across ephemeral river is done in such a way that finer particles flow with flood and the coarser sands deposit behind the weir. However, as the reservoir eventually silted, the weir is raised once again for next satisfying floods.

There is no scientific evidence available previously on criteria or model that can be used as a guide on successive incremental construction of weir while optimizing water storage potential based on desirable coarse sand grade collected behind the weir.

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Studies on water storage in sand are few. Miglio et al. (2009) studied the aggradation and degradation in fluvial beds morphology in a narrow flume. Renaat de Sutter and Krein (2001) performed sediment transport simulation during flood events using laboratory and field experiments to understand suspended load transport. Pal et al. (2001) studied development involving soil detachment. They examined the different methods, mechanisms and conditions of sediment movement in fluid-grain mixtures. Other approaches in understanding fluid-grain mixtures have been examined. Picouet et al. (2001), Reid and Frostick (1987) studied estimation of change in sediment concentration in a river, while Wright and Parker (2005) present numerical modeling formulation for simulation of the longitudinal profile and bed sediment distribution in sand-bed rivers. The study analysed downstream decrease in bed slope and a down-stream decrease in bed sediment diameters. Size grades are shown to be hydraulically controlled in many studies which increases prospect of deriving a physically deterministic model in sediment transport. Longitudinal variations in the size and sorting of bed material along six arid region mountain streams were studied by Rhoads and Urbana (1989). The study uses regression analysis to investigate downstream patterns in mean grain size and sorting of bed material. Mean grain size declines exponentially along four of the six streams. Hut et al. (2008) described model to understand groundwater flow around sand water reservoir. However, complexity due to dynamics and laws which govern sediment transport and deposition probably make it difficult to progress on this topic develop.

The present paper thus provides preliminary results of current research in laboratory flume experiment highlightting role of weir heights on grade of sediment deposition in sand water reservoir.

MATERIALS AND EXPERIMENTAL PROCEDURE

Experimental setup

The experiments were conducted using a non-recirculating, sediment-feed, tilting flume of 2 m long, 30 cm wide and 30 cm deep. Sediment was not recirculated to simulate the condition of imposed sediment load from catchment slope. The flume was built in Mechanical Skills laboratory of the Tshwane University of Technology, Pretoria, South Africa with see-through materials. A hopper designed to hold sediments was built and feeder belt-conveyor of 670 mm long having same width of flume was laid directly beneath outlet of a hopper to introduce sediments. Calibrated screws were used to support hopper in-take above conveyor belt and variable speed motor linked the drive of conveyor belt. Combination of heights adjustment of screws and motor speed controlled sediments feed rates into flume. The hopper-feeder arrangements positioned upstream of flume. Sedimentation trough made of same materials with flume was built-in tightly into walls and floor of flume downstream to hopper-feeder arrangement. Wall outlet of the sedimentation trough was slotted to hold imposed variable weir heights. The weirs were in 5, 10 and 20 mm. The floor of the sedimentation trough and flume were roughening with 2.36 mm sand grains spread evenly and carefully glued to the surfaces to simulate impermeable channel bed surface and channel roughness. A water reservoir, for the collection and supply through water pump, and in-line electromagnetic flow meter for precise measurements of flows through apparatus were installed. Figure 1 shows a photographic plate of the apparatus.

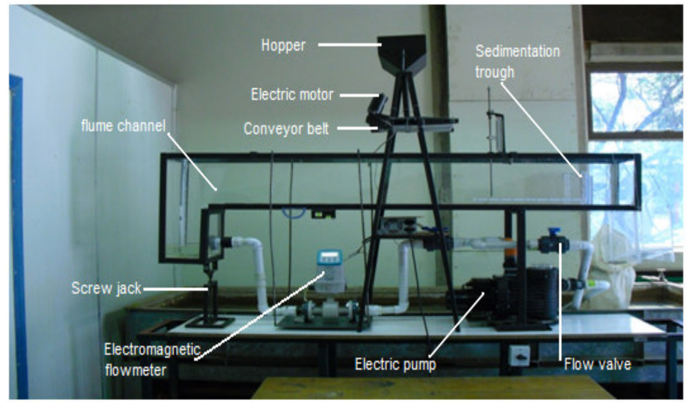

Figure 1. Experimental setup of sediment transport in sand water storage.

Alluvial materials for experiments

The sand materials used for study comprised of mixture of grain sizes collected from conventional catchment of sand water storage reservoir. At early stage of all experiments, the sand samples collected were screened off grain sizes more than 6.7 mm. The mixed sediments had a natural grading with D_{50} = 0.1 mm, D_{75} = 2.0 mm, D_{25} = 0.52 mm, and D_{max} = 6.7 mm. While the subscript is the cumulative percentile of the particle-size distribution as shown in Table 1.

Procedure and measurements

Experiments were conducted in a 0.45 by 0.3 m section of sedimentation trough. At the beginning of each experiment, bed slope, S_o was fixed at 1% and the sediment supply system was filled with 1 kg mixed sediments. Then water was allowed into flume with imposed weir. The flows were controlled by regulating in-line valve and a bypass valve and flows measured by electromagnetic flow meter. The water flows were allowed to stabilize with imposed weir at the downstream end of sedimentation trough. The hopper and belt feeder arrangements from upstream side introduced mixed sediments into flume channel. We carried out set of experiments at a given sediment flow rates, set at a constant of 54 g/s, varying the water flow rates from 6.2 - 8.1 m^3/h with each imposed weir. Then water discharged to the flume was shut off when the sediments reached equilibrium with flows in sedimentation trough with imposed weir. Sediments trapped behind the imposed weir in the sedimentation trough were carefully washed out into separate pans, dried and sieved for each run of experiments. The experimental run was replicated with other weir sizes. Particle-size distributions of deposited sediments were determined using the method described in (Bunte and Abt, 2001) and correspoding coefficient of uniformity (C_u) determined using equation 1.

Degree of uniformity in sediment is measured by coefficient of uniformity (C_u) of grain size distribution defined as the ratio of the particle diameters d_{60} to d_{10}. C_u less than 5 is soil defined as uniform grade (Wilun and Starzewski, 1972).

Table 1. Particle size distribution of mixed sediment feed.

Size (mm)	Per cent by weight	Cumulative per cent
0.075 - 0.31	19	10.4
0.3 - 0.6 44	31.4	
0.6 - 2.0 16	74.7	
2.0 - 4.75	21	100

Table 2. Experimental data obtained under imposed weir heights with flow rates.

Sample	Discharge, Q (m^3/h)	Height, H (mm)	C_u (d_{60}/d_{10})
RUN 7	6.2	10	6.59
RUN4	7.2	10	7.83
RUN10	7.5	10	6.84
RUN 1	8.1	10	7.93
RUN 8	6.2	15	4.19
RUN 5	7.2	15	5.12
RUN11	7.5	15	4.72
RUN2	8.1	15	5.06
RUN 9	6.2	20	3.39
RUN 6	7.2	20	3.81
RUN12	7.5	20	3.74
RUN 3	8.1	20	4.32

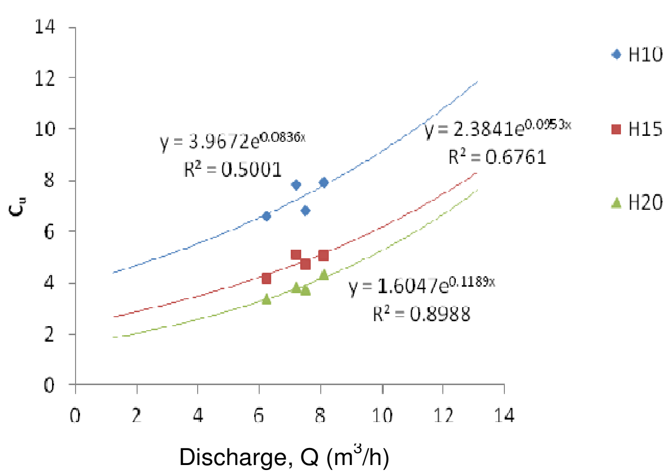

Figure 2. Discharge in relation to coefficient of uniformity of deposited sand.

$$C_u = d_{60}/d_{10} \quad (1)$$

Where: d_{60} and d_{10} are particle diameter at which 60% and 10% of soil weight is finer.

OBSERVATION AND RESULTS

Grain size distributions of deposited sediment in sedimentation trough with imposed weir of 10 mm were carried out in the first series of experiments and analysed with flow rates varied from 6.2 - 8.1 m^3/h following by other subsequent weir heights. The flow retardation produced a backwater and coefficient of uniformity of sediment deposition varied with flow rates and height of weirs (Table 2). The Table 2 shows coefficient of uniformities of deposited sediments obtained after treatments. Figure 2 presents graphical representations of the plot of coefficient of uniformities against flows at various height of weir used while Figures 3, 4 and 5 show the individual grain size distribution curves of deposited sediments at specific height of weirs. As shown in Figure 2, the empirical model of coefficient of uniformity is approximated by exponential function at weir height of 10 mm, although, in places, there was deviation departing from exponential trend. As expected, the correlation functions for other weir heights are similar. We observed a slow exponential increase as a typical behaviour in Figure 2 with relation coefficient for weir at 10 mm greater than 5. However, increase in weir height shows improved relation coefficients for the weirs of 15 and 20 mm which were greater than 0.6 and 0.8, respectively.

Table 2 shows gradual decreases in coefficient of uniformity of deposited sediments as height of weir increases. These may reflect a consistent tendency to the sediment phase to become self-organized.

In flow, natural sediment particles are never transported at same rates however they have intrinsic characteristics in distributions of grain sizes. Most desirable grain size distribution for sand water reservoir is uniform grade sand. In principle, sand water storage with uniform grade sands can store 50 - 60% of its volume in water. It is noted that, vertical sorting profiles showed a downward coarsening trend within the bed forms. Three processes can be attributed to forming such coarse bed layers which are; avalanching effect, partial transport in which most coarse materials does not engage in the transport and the winnowing of fine from trough surfaces.

Conclusions

It is possible to reproduce sedimentation development in sand water reservoir in laboratory to improve quality of grade of sand for better efficiency. In sand water storage reservoir, sediments porosity depends on grain size, the shape of the grains, the degree of sorting and the degree of cementation. Well-rounded coarse-grained sediments usually have higher porosity than fine-grained sediments, because the grain does not fit together well. Poorly sorted sediments (sediments contains a mixture of grain sizes) usually have lower porosity because the fine-grained fragments fill the open spaces. Uniform grade sand water storage may store 50 - 60% of its volume in water.

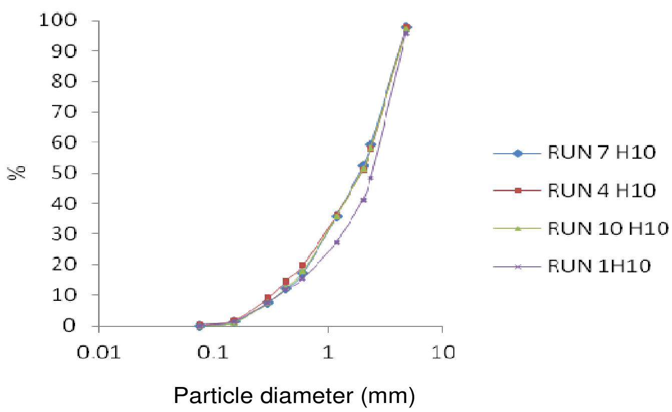

Figure 3. Particle size distribution curve at weir height of 10 mm.

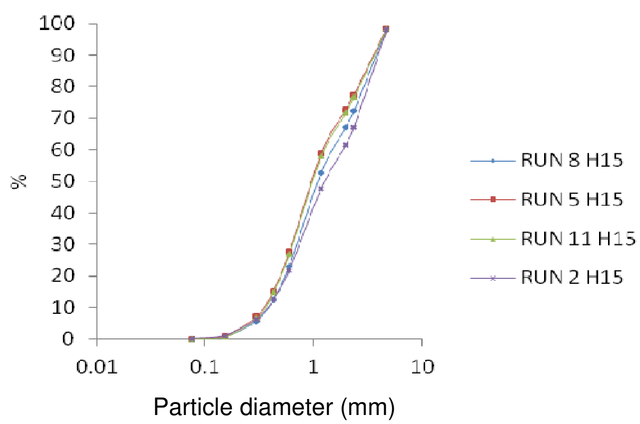

Figure 4. Particle size distribution curve at weir height of 15 mm.

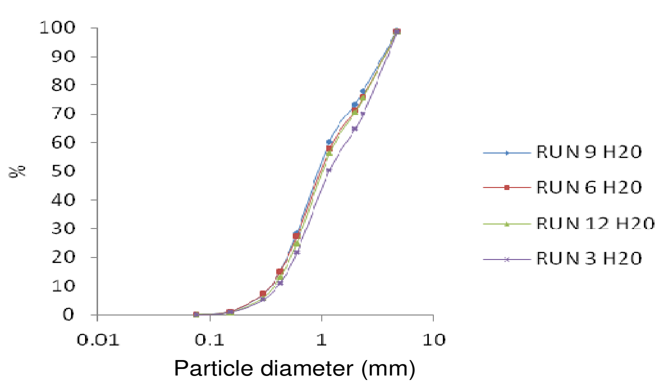

Figure 5. Particle size distribution curve at weir height of 20 mm.

Although the amount of sediment derived from water catchment is influenced by both storm and drainage basin characteristics which may be difficult to simulate in laboratory. Poor sediment supply could lead to formation of an armour layer. Further investigations should show the influence of different permeabilities of existing deposits has on deposited grade. It can be assumed that differences in permeability largely control the run out distance and lateral spreading of sediment flows.

The relations can be used to predict successive phased increment of weir for improved efficiency in sand water storage when hydraulic dynamic similarity and hydrogeological conditions are considered.

ACKNOWLEDGMENT

We wish to thank Tshwane University of Technology for providing the facilities and financial aid to carry out this study.

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