THE EFFECT OF SURFACE ALBEDO AND GRAIN SIZE DISTRIBUTION ON EVAPORATION LOSSES IN SAND DAMS

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Abstract

Sand dams are very useful in arid and semi arid lands (ASALs) as facilities for water storage and conservation. Soils in ASALs are mainly sandy and major water loss is by evaporation and infiltration. This study investigated the effect of sand media characteristics, specifically surface albedo, grain size and stratification on water table recession using experimental model. Tanks of 220 litres capacity and 0.9 m depth were set as evaporation media at the JKUAT weather station in Kenya. Experimental media investigated were; fine ballast, fine sand, coarse sand, *in situ* sand and stratified combination. Surface albedo were varied by painting top sand media with colours such as white, grey and natural brown sand colour as a control. Albedo were indexed using luminance factor. The study concluded that evaporation losses are inversely proportional to the albedo of the evaporating surface measured in terms of luminance factor. The relation between water table recession in porous medium and pan evaporation is an exponential decay curve. The study showed that stratification of media have significant influence on water loss particularly, if the overlying material is courser than the underlying layers.

Key words: Sand dams, evaporation, surface albedo, ASAL, water conservation

1.0 Introduction

Development of evaporation mitigation technologies through search for appropriate water conservation measures has been at the center of water resources management studies in arid and semi arid lands (ASALs) around the globe. A range of evaporation control products have been developed and in some cases are commercially available to control evaporation losses from water storages. These products range from floating covers, modular covers, shade structures, chemical monolayer covers and biological and structural/design methods (Craig *et al.,* 2005). However, problem of water conservation in ASALs, particularly in developing countries, still persist because of high cost of implementing these high tech methods. Therefore, appropriate technologies which heavily borrow from traditional knowledge is more appropriate in ASALs of developing countries.

Major factors which are known to influence rate of evaporation from open water storage facilities are: temperature, solar radiation, wind, soluble solids and relative humidity and nature and shape of surface. Details of such factors are found in standard hydrologic literature, e.g., Frank (1964). The theory of albedo can be traced to the application of energy balance principles in evaporation studies (Fritz and McDonald, 1949). Colour and reflective properties of the surface (albedo) is one of the parameters that can be used to characterise nature of evaporating surface. By definition, albedo is the ratio of reflected solar energy to the incoming radiation or alternatively a measure of reflectivity of a surface or body. The theoretical explanation of the effect of albedo on evaporation can be derived from the fact that evaporation as a phenomenon means change of state of molecules of water from liquid to gas and this requires energy input (latent heat of vaporisation) which is provided by the direct radiation of the sun. Therefore, other factors remaining constant, the rate of evaporation from a surface depends on the amount of solar energy retained in the substance which can be measured by magnitude of its abedo. Therefore, many classical energy balance evaporation studies have factored in albedo constants in their expressions (e.g. Penman., 1948). This justifies the need for understanding the effect of albedo for various evaporating surfaces like sand surfaces.

Semi-arid, arid and hyper arid parts of Kenya comprise 82% of the country's total surface area (GOK, 1995). Rainfall received in these areas is between 200 mm and 800 mm per year, while evapotranspiration losses are in the order of 1500 mm per year. Permanent water sources such as lakes and rivers are scarce. Drought occurrences are common and this situation creates permanent pressure on demand for water (Hai, 1997). Kenya's arid zone supports approximately 25% of the human population and more than 50% of livestock, thus exerting a greater need for provision of adequate water (JICA, 1992; GOK, 2001; 2003).

Sandy soils which occupy most of ASAL regions are known to have high porosity which can store substantial amounts of water. This property is usually exploited by people living in arid areas to harvest flood waters and store them beneath sand for utilisation during dry periods. Structures traditionally deployed for run-off harvesting along the river beds in ASALs in Kenya are sand-filled structures commonly referred to as sand dams (ASAL Consultants, 1996). Sand dam is a special type of sub-surface structure built across a seasonal river. It provides a means of increasing water storage by accumulating sand and gravel upstream of the dam within which water is stored. Though water stored in sand dams is not exposed to direct evaporation, further minimisation of evaporation water loss is still desirable if the water demand of ASAL regions is to be met through water conservation.

Some of the suggestions given to mitigate against the high evaporation losses in ASAL environments by previous investigators include the removal of phreatophytes along river beds (Hellwig, 1973a, 1973b). This approach is bound to meet stiff resistance from environmentalists due to its negative environmental impact. Other ways in which evaporation losses on sand surface can be minimised include the use of polymer material as well as covering the surface with polythene sheeting. Both approaches are fairly costly and laborious. Additionally, the polymer material can retard the efforts to trap water in the sand media in consecutive seasons by creating an impervious layer.

Previous studies on evaporation phenomenon in saturated sand media concentrated on finding the critical depth at which evaporation ceases within sand media (Hellwig, 1973a-c; Mburu, 1989), however, these studies did not explore ways of enhancing efficiency of water storage within the sand media. This study investigated how reservoir storage efficiency may be improved by understanding the influence of sand reflectivity, grain size considerations and stratification on evaporation. Changing sand reflectivity is a relevant approach in overcoming water storage losses by simply spraying artificial colours on sand surface layer. Surface colour exerts its influence through albedo effect, which in turn, affects the net radiation (Hanks *et al.,* 1980). Additionally, the sand grain size used by earlier investigators was a mixture of various grades compared to the situation in this investigation which a uniform and stratified media cases are considered.

The significance of this research is that the results have a great potential to make significant contribution in the way sand dams are to be designed and constructed in the near future so as to improve storage efficiency.

2.0 Methodology

The investigation was by a physical model set up in Jomo Kenyatta University of Agriculture and Technology (JKUAT). The experimental set up was located within the perimeter of the university's weather station: latitude 01^0 05' 23"S, longitude 37^0 00' 29"E at an elevation of about 1538 m above sea level. Tanks of volume 220 litres and depth of 0.9 m were filled by sand of different sizes and top surfaces painted in various colours. Rate of water recession in the sand beds, were monitored by piezometer tubes attached to the tank surfaces. Typical experimental set up is illustrated in Figure 1.

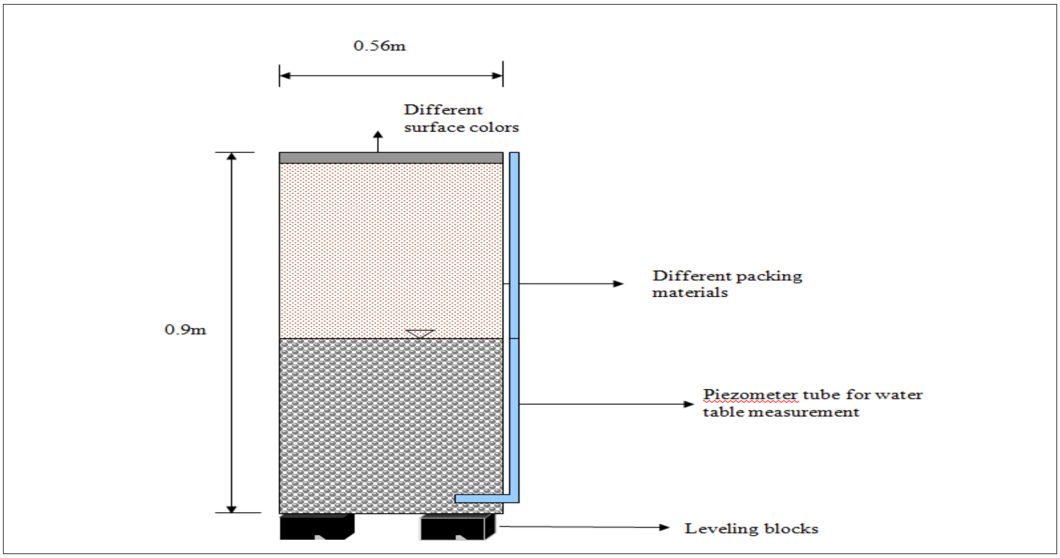

Figure 1: An experimental sand bed tank set up

The investigation procedure involved a four-step approach:

1. Investigation of effects of varying sand albedo on water table recession and choosing the case with minimum water loss as best case
2. Correlating data in case (1) and pan evaporation data measured at the same site.
3. Investigation of the effect of varying grain size on water table recession based on the best reflective surface as defined in step (1) .
4. Investigation of effects of media stratification on water table recession based on best reflective surface as defined in step (1).

Table 1 summarises the experimental design as used in this study. It assumed that water table recession is as a result of evaporation loss only as the experiment was done in tanks which do not allow seepage losses.

In an attempt to isolate the surface albedo with least evaporation potential, four media materials including *in situ* sand, fine sand (0.6-0.1 mm), coarse sand (0.6-2 mm) and fine ballast (6 mm) were studied as the starting point in case 1. Only grain size ranges were used to classify media material, for example, sand retained on sieve No. 30 was taken as course sand while those passing as fine. Ballast used was uniform particle size to fit ballast specification trend in Kenya. For each media material, six tanks were packed and experiments observed in turn for a period of two weeks. Three colour surface characteristics (brown, white and grey) were chosen on the basis of their resemblance to natural colours of media material and white being extreme boundary condition of albedo scale. The media surface colour was established by spreading the surface with already painted media material. Stratified sand bed layers of *in situ* sand overlaying ballast, and ballast overlaying *in situ* sand were also studied.

Table 1: Summary of experimental design

Experimental case	**Media type (equal trials per each case)**	**Grain size**	**Surface characteristics observed**
Case 1 Investigation on the effects of varying sand albedo on water table recession and isolating the best performing colour surface	*In-situ* sand	Mixture	Brown, grey, white
	In-situ sand overlying ballast	Mixture	Brown, grey, white
	Fine ballast	6.0 mm in diameter (Commercially referred to as 1/4inch)	Brown, grey, white
Case 2 Correlating data in case (1) and pan evaporation data measured at the same site	*In-situ* sand	Mixture	Brown, grey, white
	In-situ sand overlying ballast	Mixture	Brown, grey, white
	Fine ballast	6.0 mm diameter (Commercially referred to as 1/4inch)	Brown, grey, white
Case 3 Investigating effects of varying grain size on water table recession based on the best performing colour in case 1	*In-situ* sand	Mixture	White
	Coarse sand	(2.0 mm- 0.6 mm diameter)	White
	Fine sand	(0.6 mm -0.1mm diameter	White
	Fine ballast	6.0 mm diameter (Commercially referred to as 1/4inch)	White
Case 4 investigation of effects of media stratification on water table recession based on best reflective surface as defined in step (1)	*In-situ* sand	Mixture	White
	Course sand over ballast	*Mixture	White
	Ballast over *in-situ* sand	*Mixture	White

*Note: * Mixture means stratified media, whereas Mixture is naturally deposited sand*

The albedo surface characteristic of each colour was determined by measurement of luminance factor of the surface colour material using reflectance spectrophotometer. Test procedure involved calibration of the instrument by setting 100% reading with white magnesium oxide and 0% reading with black surface. The luminance of a surface was then determined relative to the luminance of a diffusely reflecting white surface (magnesium carbonate).

In cases 3 and 4, the white media was maintained while other parameters were being varied. During the experimental run for each media material, the water table recession of the sand bed and potential evaporation from USWB class A pan were recorded at a daily time interval.

3.0 Results and Discussion

Results of Case 1 are shown in Figure 2 to 4. All the figures show that the rate of water table recession is high at initial time and later reduces as the depth of water table below the tank's top surface increases. This is in agreement with natural phenomenon of increased resistance to groundwater extraction by evaporation as the groundwater table recedes from surface. The observation is also in agreement with reported observations by Hellwig (1973c), that showed the evaporation rate decrease from 50% of that from an open surface when the water table was 30 cm below the surface to 10% when the water table was 60 cm below the surface. All the three trials in Case 1 have similar arrangements of the resulting curves if classified by colour. The upper bound for each family of curves is white surface and the lower bound was grey. The distinction of the effect of surface colour on water table recession is minimal at near surface. This means that the effect of albedo is insignificant if water table is at or very close to the surface. The media surface colours were distinguished by their measured luminance factor (LF) as indicated in Table 1. The values in Table 1 show that white (brighter) surface is generally a better reflector than brown or grey (dull) surfaces. Table 1 shows values defined as critical depth. These are extracted depths from Figure 2 to 4 corresponding to point at which rate of decay on water table recession is considered minimum for each surface colour. The minimum values as referred to here is the point at which rate of change of decay approaches asymptotic trend. However the water table continues to recede after 12 days but at a much slower rate. In all cases the critical values are highest at grey surface and lowest at the white surface. This is in agreement with the principles of evaporation that relies on the supply of energy for vaporisation. Higher luminance factor implies low heat absorption and low energy supply for vaporisation. This is a clear indication that if brighter media materials are used in sand dams, there is bound to be enhanced efficiency of water storage. Though sand dams are known to build up naturally, evaporation losses in them can be reduced by encouraging artificially constructed sand dams in ephemeral streams rather than waiting for slow natural accumulation of natural sand. It should be noted that the three colours investigated here (white, brown and grey) do not necessarily correspond to natural colours of sand in any particular region. However, for comparative purposes, it can be observed that most river sand are brown, ocean sands are close to white and quarry dust sand are grey. Therefore, to compare different regional evaporation losses with different colours of sand, the argument must take cognisance of need to hold constant other factors affecting evaporation in region being compared.

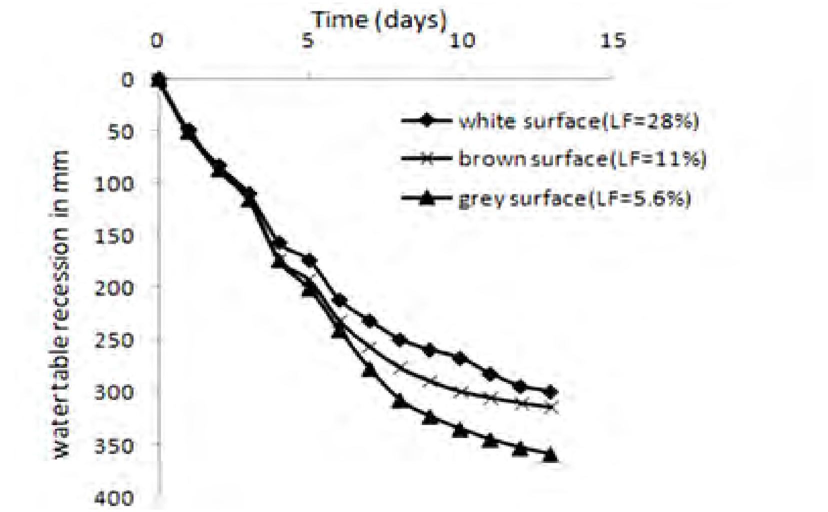

Figure 2: Water table recession (piezometric reading) in in situ sand bed

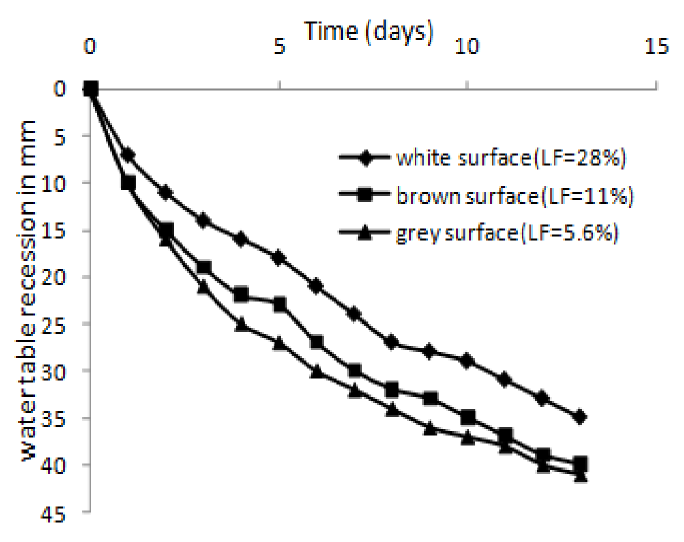

Figure 3: Water table recession (piezometric reading) in fine ballast media bed

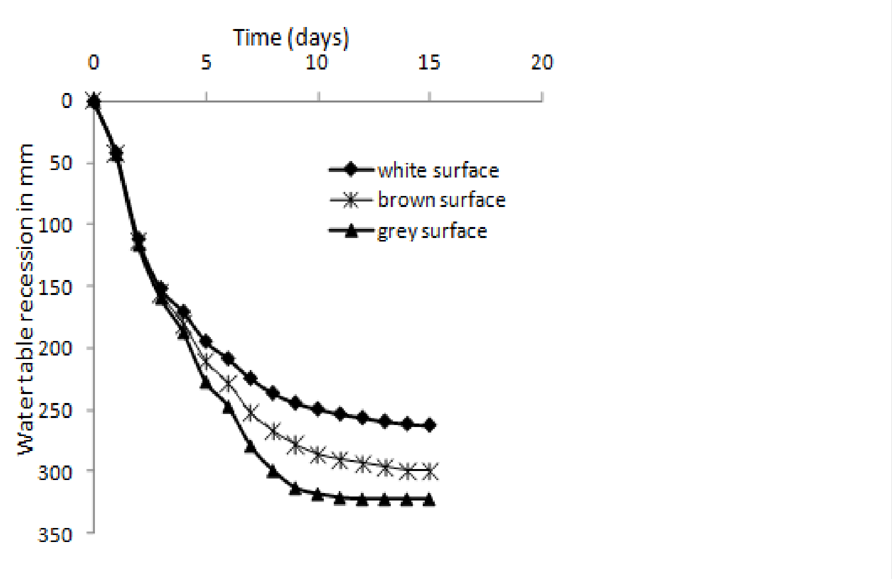

Figure 4: Water table recession in stratified bed: in-situ sand underlain by ballast

Table 2: Critical depths at which change in water table recession is minimal for a combination of surface colours and bed material

Media material*	**Porosity (%)**	**Surface colours**		
		White L.F=0.28	Brown L.F= 0.11	Grey L.F 0.056
In-situ sand	36	300mm	315mm	360mm
Fine ballast	45	35mm	40mm	41mm
In-situ sand underlain by ballast		255mm	300mm	325mm

**Classification conforms to grain size ranges given in Table 1*

Pan evaporation data which were observed simultaneously with Case 1 were correlated with water table recession data and Figures 5 to 7 show these results. Similar to observations in Case 1, all figures 5-7 displayed gradual exponential decay with high correlation statistics (R^2). This confirms the assumption that water recession in experimental tanks was simply a function of evaporation. Though pan data and experimental media are not having same exposure, both behave similarly under same climatic factors.

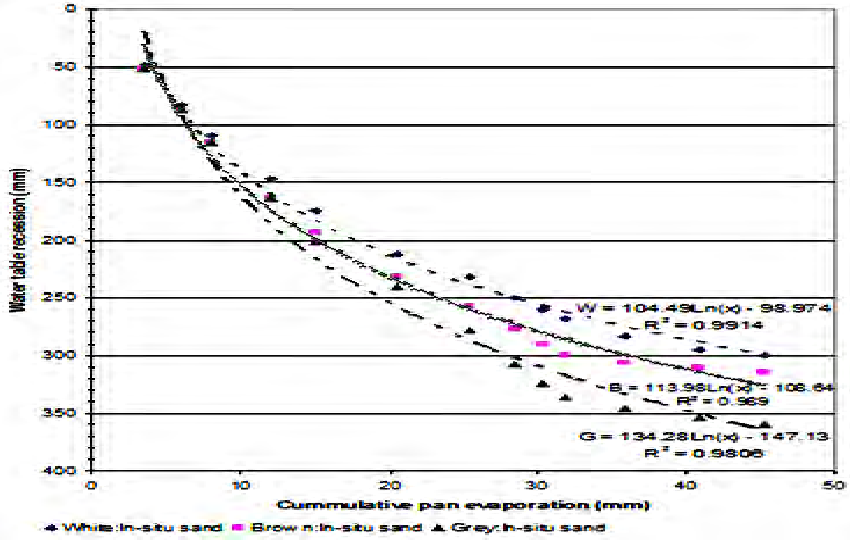

Figure 5: Effect of cumulative evaporation on water table recession: case of different colours of in situ sand

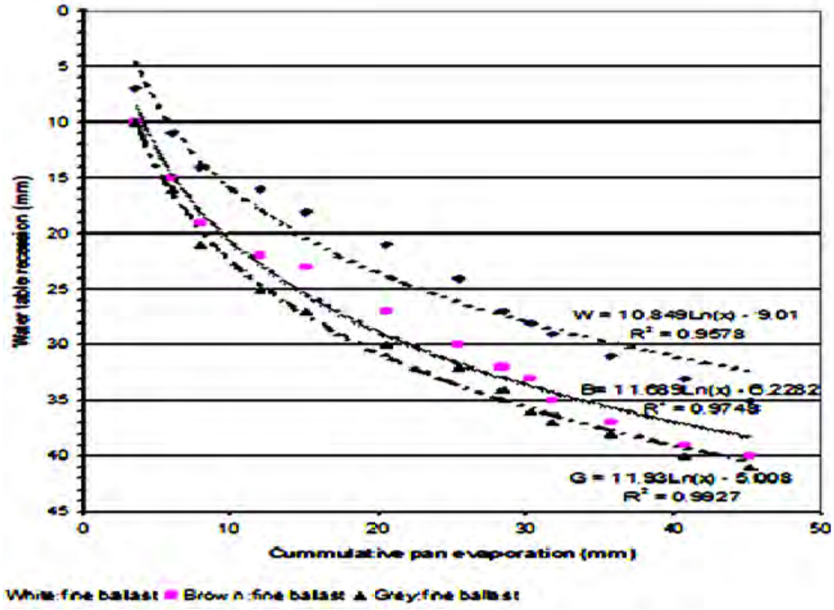

Figure 6: Effect of cumulative evaporation on water table recession: case of different colours of fine ballast.

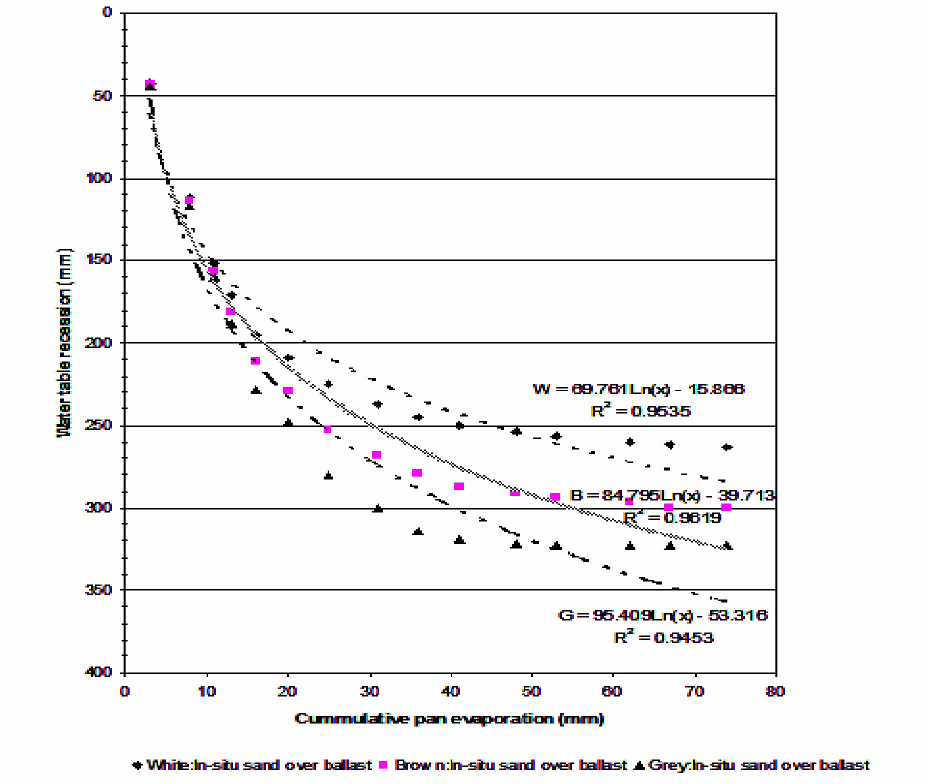

Figure 7: Effect of cumulative evaporation on water table recession: case of different colours of in situ sand over ballast

In an attempt to model water table recession and pan data relationship, trend equations were fitted on Figure 5-7. General inspection shows that the trend of these curves is a decay curve with a generalized formula of the form indicated in equation 1.

$$H = a + b\ln X \quad \text{..(1)}$$

where,
H = the water table recession in mm.
a = an intercept defining the conditions at the start of the experiment.
b = rate of decay.
X = the cumulative pan evaporation (mm).

X value, being pan evaporation data, is a manifestation of the sum total effect of all meteorological factors which affect evaporation (e.g., temperature, relative humidity, wind speed, solar radiation e.t.c.). The decay curves (Figure 5 to Figure 7) show similar trends to Figures 2 to 4 with white surfaces and grey surface forming the upper and lower bound curves. This similarity of trends for Figures 2 to 4 and Figures 5 to 7 is the relation between accumulative time since evaporation started and accumulative evaporation itself assuming no effects of recharge. Table 2 shows physically extracted values of b as defined in equation 1 from Figures 5 to 7. Because of distinct location of these curves by media surface colours, it can be safely assumed that 'b' values are a function of luminance values. It also noted that these decay curves are not unique as their location is also a function of location parameter 'a' which is a theoretical value of water table at cumulative evaporation equal zero. This is not a physical parameter of media and therefore difficult to estimate. It therefore requires that family curves describing 'a' values for a particular field antecedent condition be established to operate the model which is beyond the scope of this study. However, for real surface which correspond to experimental set described in this study, the 'a' and 'b' values written against the curves can form an intelligent first guess for estimating water table recession if pan data in available. The assumptions under which this experiment was done must be taken into account when applying these parameters. For example the assumption that the water table coincides with ground surface at the end of rains and recedes thereafter as a function of evaporation only may not apply all the times in real field conditions. There is need to verify the accuracy of the curves with corresponding field data.

Table 3: 'b' values for different media and luminance factor

Luminance factor	**'b' values**		
	Fine ballast	***In-situ* sand**	***In-situ* sand over ballast**
0.28	10.85	104.49	69.76
0.11	11.69	113.98	84.80
0.056	-	134.28	95.41

Case 3 was investigated by observing water table recession on media of different grain sizes while keeping the surface colour constant, in this case the best reflective surface which is white. Table A-1 in Appendix A shows the field data which is summarised in Table 4. Volume lost as a percentage of total volume as given in Table 4 is estimated as simple ratio of maximum accumulated water table recession value for each grain size to total media depth which is 900 mm according to Figure 1. Therefore, Table 4 indicates that fine sand is found to lose 41% of the water stored as compared to only 3.8% of fine ballast. *In situ* sand loses 33% as compared to coarse sand 11%. This can be explained by the difference of capillarity potential of the studied media. Fine ballast has the lowest capillarity potential to convey water at a deeper water table to near surface where evaporation potential is high and so minimum loss. The opposite is for fine sand which has the highest capillarity potential.

Table 4: Effect of grain size on water loss, keeping white surface constant

Media	**Observed recession (mm)**	**Volume lost as percentage of total volume**
In situ sand	295.0	32.8%
Coarse sand (2.0 mm- 0.6 mm diameter)	95.0	10.6%
Fine sand **(**0.6 mm diameter and less)	371.0	41.2%
Fine ballast (6.0 mm diameter	33.0	3.8%

Note: Source data (See Appendix A-1)

Case 4 was investigated by observation of water table recession in stratified media. Observed data are appended in Table B-1 of Appendix B. Table 5 provides a summary of observed data in Table B-1. Column on volume lost in Table 5 is defined as was defined in the foregone Case 3. The results indicate that stratification of media have significant influence on water loss particularly, if the overlying material is courser. Table 5 shows minimal water loss (5%) when ballast is overlying media. This can be explained by discontinuity of capillarity force by the overlying ballast. This encouraging result indicate that large evaporation losses in sand dams can be reduced by having stratified medium arrangement with top courser layer. Though this arrangement may not maximise on available storage volume due to low porosity of lower medium, the saving on evaporation loss might cancel that disadvantage.

Table 5: Effect of stratification on water loss, keeping white surface constant

Media stratification	**Observed recession mm**	**Volume lost as a percentage of total**
In situ sand overlying ballast	263.0	29%
Coarse sand overlying ballast	187.0	21%
Ballast over *in situ* sand	44.0	5%

Note: Source data (See Appendix B-1)

4.0 Conclusions

(i) The surface albedo has a significant influence on evaporation. Evaporation losses are inversely proportional to the albedo of the evaporating surface measured in terms of luminance factor. Bright surfaces (white) reduce evaporation while darker surfaces enhance evaporation.

(ii) The experimental relationship between water table recession and pan evaporation is an exponential decay curve.

(iii) Grain size has significant influences on evaporation in a sand dam. Large grain sizes (mean diameter 6 mm) lost only 4% of stored water through evaporation while fine grains (<0.6 mm) lost 41% of drainable volume.

(iv) Stratification of media has significant influence on water loss particularly, if the overlying material is courser. The loss appeared to depend on the top layer media. This means that evaporation water loss is greatly influenced by capillarity characteristics of the top medium in a stratified arrangement.

Acknowledgement

The researchers sincerely appreciate technical support given by the staff at the JKUAT weather station.

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APPENDIX A

Table A-1 Source data for Table 4
Luminance factor 0.28 –white surface

Date	Fine ballast (6.0mm diam)	Coarse sand (0.6-2.0mm diam)	*In-situ* sand (mixture)	Fine sand (less than 0.6mm diam)
2/6/2006	0.0	0.0	0.0	0.0
3/6/2006	4.0	30.0	50.0	155.0
4/6/2006	11.0	43.0	95.0	210.0
5/6/2006	17.0	50.0	138.0	260.0
6/6/2006	19.0	59.0	168.0	265.0
7/6/2006	21.0	63.0	195.0	270.0
8/6/2006	22.0	67.0	226.0	278.0
9/6/2006	23.0	71.0	237.0	300.0
10/6/2006	25.0	74.0	257.0	321.0
11/6/2006	27.0	78.0	267.0	337.0
12/6/2006	28.0	81.0	275.0	344.0
13/6/2006	31.0	86.0	280.0	353.0
14/6/2006	32.0	89.0	285.0	360.0
15/6/2006	33.0	92.0	293.0	366.0
16/6/2006	33.0	95.0	295.0	371.0

APPENDIX B

Table B-1 Source data for Table 5
Luminance factor 0.28 –white surface

Date	*In-situ* sand over ballast	Coarse sand over ballast	Ballast over *In-situ* sand
14/9/2006	0.0	0.0	0.0
15/9/2006	42.0	24.0	12.0
16/9/2006	112.0	47.0	22.0
17/9/2006	152.0	78.0	25.0
18/9/2006	171.0	110.0	25.0
19/9/2006	195.0	124.0	27.0
20/9/2006	209.0	140.0	28.0
21/9/2006	225.0	153.0	30.0
22/9/2006	237.0	162.0	32.0
23/9/2006	245.0	165.0	35.0
24/9/2006	250.0	169.0	38.0
25/9/2006	254.0	175.0	40.0
26/9/2006	257.0	179.0	42.0
27/9/2006	260.0	183.0	43.0
28/9/2006	263.0	187.0	44.0