# Evaporation mitigation by storage in rock and sand

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Abstract. For many countries in the world, the annual evaporation rate may exceed the annual average rainfall by an order of magnitude. Economic mitigation methods are presently of keen interest to drought-affected countries subject to climate changes. Sand filled dams have been used to reduce evaporation by storing water within the soil pores. However, the effective water storage is determined by the specific yield (the volume of water that can be extracted from a saturated soil/water matrix) which increases with grain size. A systematic suite of investigations of the role of grain size in wind-forced evaporation from groundwater storages has been completed. By monitoring the evaporation from initially saturated systems in a laboratory wind tunnel, formulations conforming to the classical Penman equation have been developed for the near surface layers of sand and rock storages. The storage materials included both igneous and sedimentary media spanning nominal sizes from 0.4 mm to 80mm. On a volumetric basis, the evaporation rate is significantly less than open water for groundwater systems below a critical depth which increases with decreasing grain size and increasing intrinsic porosity of the rock materials. At very shallow depths, the volumetric evaporation rate tends to be greater than occurs on open water surfaces, presumably because of increased capillarity and adhesion. Parameterisations have been developed to characterise these processes, are evaluated by the study data and show systematic behaviour across a range of granular materials.

Key Words: Evaporation, groundwater, capillarity, adhesion

## 1. Introduction

For many countries in the world, development is limited by available water resources. In some regions (Africa, Australia and the Middle East), the primary issue is the high evaporation rate which may exceed the annual average rainfall by over one order of magnitude. Significant climatic variations in annual average rainfalls have been observed and are a present cause for concern with regard to possible future systematic climate change. There is considerable contemporary interest in protecting present water supplies and, if possible, developing new high yield sources within these arid zones.

Watts (2005) and Ninaus (2008) present summaries of the evaporation mitigation techniques available in Australia. These include physical alterations to reservoir form, physical barriers, chemical alterations and chemical barriers. At present, none of these methods has been widely adopted as each method has specific limitations that appear to make them economically unjustifiable. For example, protective covers, which provide 100% reduction to evaporative losses, remain very expensive to install and maintain and are not economically feasible for widespread use on farm dams. In addition, there are risks (physical human and animal safety, contamination, poor water quality) associated with many of these options, some of which still may not yet have been identified

The subject of this present contribution is the performance of groundwater dams: artificial aquifers formed by storing water within the pores of poorlygraded rock and sand. This approach has not received serious consideration in Australia although naturally occurring aquifers are a major water resource in specific regions of inland Australia. Preliminary designs for Australian application indicate that the use of local materials makes these structures attractive economically. Their nature and function does not seem to pose significant risks for stock or native wildlife. Their porous nature also provides opportunities to improve the quality of captured runoff through appropriate design. A major challenge associated with water supplies in such landscapes can be the separation of flood waters from flood-borne sediments. Properly designed groundwater dams can do this effectively and efficiently.

In Africa, artificial sand filled dams (where water is stored within the soil pores) have been used to reduce evaporation for many decades (Wipplinger 1958; Nilsson 1988). Figure 1 shows one type of sand storage dam presently used in practice. These are constructed by building an impermeable wall in the path of an existing ephemeral waterway. Coarse alluvial sediments accumulate upstream of the dam wall. As the storage becomes filled with sediment, successive tiers are added to the wall gradually increasing the capacity of the reservoir (Nilsson,



Figure 1 Conceptual diagram of a sand storage dam

1988). Infiltrating water during rainfall events can be accessed via the drain to provide a sustainable water supply during times of drought. Sand storage dams can be found in Ethiopia, Kenya and South Africa, constructed with local materials and at minimal cost.

Wipplinger (1958) made careful observations of specific yield and water extractions from the Aukeigas sand dam, South Africa between 1941 and 1951. By careful water balance calculations, Wipplinger was able to quantify water level variations within the dam whilst accounting for rainfall and water extractions. Thereby, he was able to show that the evaporation rate systematically decreased as a function of water depth below the sand surface. Wipplinger (1958) deduced that evaporation virtually ceased at a depth of 0.9m below the surface.

Hellwig (1973) showed that by using coarser sand mixtures the rate of evaporation was reduced relative to fine sand. It is also well established that specific yield (the volume of water that can be extracted from a saturated soil/water matrix) increases with grain size. In spite of Hellwig's work showing that grain size plays an important role in mitigating evaporation from groundwater dams, to our knowledge there has been no systematic investigation of performance of larger grain sizes.

The texture of the surface has a significant effect on the surface evaporation rate. Wipplinger (1958) reported that water at the sand surface evaporated very rapidly. Pavia (2008) monitored evaporation rate by the change in weight of a 20mm layer of saturated sand and found that the evaporation was approximately 15% faster than that from the surface of an open body of water.

In Australia, conventional open water reservoirs in arid or semi-arid zones are formed by constructing earthen embankments across ephemeral waterways (Nelson 1985). These storages are highly vulnerable to evaporative loss and may significantly reduce flows in rivers and to lakes downstream (Baille 2008). Bennett and Peirson (2008) show that implementing groundwater dams could potentially provide more robust water supplies in Australia, particularly in the arid zones with consequent reductions in diversions from downstream receiving waters.

This present contribution describes a laboratory investigation of wind-forced evaporation in a laboratory tunnel. The primary disadvantage of laboratory investigations is that diurnal heat transfer processes are difficult to simulate. However, measurement of evaporation rate under field conditions is complicated by exposure of delicate instrumentation to weather, orographic effects and animals drinking from the test facility (e.g. Ladson, 2008, p. 48). In the following sections, we describe the measurement techniques adopted, the processing of the data gathered, the study results and, the conclusions drawn.

## 2. Method

#### 2.1 Test facility

Preliminary investigations in a small wind tunnel indicated much higher evaporation rates from sands than coarser materials (Onesemo 2007) but the results had limited reliability. In particular, very careful measurements of the volumes displaced by larger materials were required to obtain reliable measurements of the evaporation rate within sand and rock matrices. To achieve the required level of accuracy, the large-scale test facility shown in Figure 2 was designed, constructed and tested (Waite 2008).

The test facility is a timber wind tunnel 0.9m wide and 0.6m high with air drawn through the tunnel by a large fan. Flow straighteners ensure a uniform velocity distribution at the inlet. A Perspex tank 1.2m long, 0.3m wide and 0.4m deep was set within the floor of the tunnel with the upper lip of the tank flush with the tunnel floor.

A piezometer tube was fitted to the floor of the Perspex tank and connected to



Figure 2 Side view of the test facility

a 115mm diameter by 400mm deep stilling pot. Water level within the stilling pot was monitored using an automatic point gauge which continuously monitors the surface with an accuracy of 0.1mm. A DC-powered potentiometer fitted to the drive shaft of the point gauge provided an analogue voltage signal that was continuously recorded by a conventional PC-based data acquisition system. Careful testing of the entire system showed that the potentiometer output was a linear function of water level within the tank.

## 2.2 Test materials

Four materials were tested during this investigation. Photographs of each are shown in Figure 3 and their physical properties are summarized in Table 1. The mean diameter ( $D_{50}$ ) and size ranges were determined by sieving for the sand and 10mm basalt and by physical measurement for the 80mm materials. Mean porosity was determined by carefully measuring the volume of water required to fill the tank (including any initial moisture), leaving the covered tank to stand overnight and adding any additional water required to refill the tank. Specific yield was determined by measuring the volume that could be drained from the tank after the mean porosity determinations. The mean saturation loss is the difference between the mean porosity and the mean specific yield. All these quantities are expressed as a proportion of the total tank volume in Table 1.

The high mean porosities associated with the 80mm rock are associated with their relative large size in comparison with the tank width as well as rock porosity. The mean specific yields highlight the superior performance of larger materials in terms of recovery of water by drainage from the matrix. The distribution of mean saturation losses are as anticipated. It is interesting to note the very similar mean specific yields of the 80mm materials, perhaps indicating that the volume contribution of the sandstone pores amount to  $\sim 7\%$  of the total volume.

#### 2.3 Test procedures

Each test material was installed within the test facility and fully saturated. A

Material	D <sub>50</sub> and range (mm)	Mean porosity (%)	Mean specific yield (%)	Mean saturation loss (%)	Temp. (°C)	Relative Humidity (%)
Empty tank	-	100	100	0	10.3-31.5	18-89
Sydney Sand	0.40 (0.075	46	17	29	13.5-23.6	35-93
	to 2.0)					
10mm Basalt	10±0.6	46	41	6	9.7-21.7	28-96
80mm Basalt	80±10	50	47	3	9.3-32.0	14-99
80mm Sandstone	80±10	57	46	11	16.1-27.6	44-96

Table 1 Summary of the physical properties of the test materials and test conditions



Figure 3 Test material used during this investigation. Upper left: sand; lower left: 10mm basalt; upper left: 80mm sandstone; lower right: 80mm basalt.

constant wind of  $6.9\pm0.2$ ms<sup>-1</sup> at the air cavity mid-height was maintained through the wind tunnel for a period of days to weeks. The fall in water level within the test facility was monitored at two minute intervals by the point gauge and data acquisition system (Lee 2009). A control test with the tank only containing water was also completed.

The physical size and air flow rates of the test facility made it physically impossible to install it within a controlled environment room. Consequently, it was necessary to account for diurnal variations in temperature and humidity as well as variations between individual tests. This was accomplished as follows: hourly environmental data for each test period was obtained from the Australian Bureau of Meteorology weather station at Observatory Hill, approximately 5km away. These measured temperature and relative humidity data were subsequently used to compute the psychrometric coefficient, the slope of the saturation water vapour pressure curve, the surface saturation vapour pressure and the vapour pressure in the air. The raw data obtained from all tests is presented in Figure 4.



Figure 4 Depth indicated by the piezometer as a function of time for the different test materials: pluses, open water; diamonds, sand; downward pointing triangles, 10mm basalt; circles, 80mm sandstone; upward pointing triangles, 80mm basalt. The grey dashed line shows the Wipplinger (1958) data at the same depth. The crosses show the open water level variations increased by a factor of 2.

# 3. Results and Discussion

## 3.1 Preliminary observations

The test programme associated with this investigation was very demanding in terms of the time required to complete each test. As shown in Figure 4, capture of adequate representative data could take up to one month. Although repeat testing is desirable, to date there has not been sufficient opportunity to run a complete set of duplicate measurements. However, the suite of observations for the different test conditions is self-consistent yielding the following observations with regard to the data shown in Figure 4:

- 1. The evaporation rate systematically decreases with increasing grain size.
- The evaporation rate systematically decreases with increasing depth beneath the surface.

- 3. The more porous sandstone shows a systematically higher evaporation rate than the low porosity basalt.
- 4. As would be anticipated, the evaporation rates above the 80mm rock matrix are very similar to those of open water. Near the surface, but just inside the granular matrix, the rate of depth increases by a factor of approximately 2 because of the volumetric effect of the rock porosity which is roughly 0.5.
- 5. The surface evaporation rate for sand simulated during these experiments is much greater than the observations of Wipplinger (1958)

#### 3.2 System characterisation

Neglecting radiative fluxes, energy fluxes due to other constituents and changes in surface temperature on evaporation rate (Brutsaert, 1982, Sections 6.1 and 10.2), the evaporation rate E (mm.day<sup>-1</sup>) can be expressed in a form developed by Penman (1948):

$$E = \frac{\gamma}{\Delta + \gamma} f(U)(e_{sat} - e_a) \tag{1}$$

where  $\gamma$  is the psychrometric coefficient in mbar.K<sup>-1</sup>,  $\Delta$  is the slope of the saturation water vapour pressure curve in mbar.K<sup>-1</sup>,  $e_{sat}$  is the surface saturation vapour pressure in kPa,  $e_a$  is the vapour pressure in the air in kPa and f(U) is a dimensional (mm.day<sup>-1</sup>.kPa<sup>-1</sup>) function of the wind velocity above the surface. Note that f(U) is influenced by the surface roughness.

The term f(U) would be anticipated to remain independent of depth for a tank containing only water. By measuring evaporation from the empty tank, f(U) was computed for the constant wind velocity used during the experiments. The data obtained from almost six days of measurements, with the temperature and humidity-dependent corrections implied by equation (1), yielded the depth profile for f(U) shown in Figure 5. No systematic variation in f(U) with depth can be observed and the entire data set yields a mean value of 22.3 with a standard error 1.27.

#### 3.3 Evaporation from granular materials

With the facility filled with sand or gravel, evaporation will cause the level to fall in proportion with the specific yield  $(S_y)$  of the material. Greater sheltering from wind would be anticipated to decrease the volumetric evaporation rate  $(E_v=S_yE)$  in finer grainer materials. However, increased capillarity-related effects in finer grained materials would be expected to increase  $E_y$ . At present, any means of distinguishing sheltering processes from those that are capillarity-related is unknown. Consequently, we are forced to use a bulk function *G* which quantifies the effect of the granular material on the evaporation rate. We rewrite equation (1)



Figure 5 Variation of the function f(U) determined from the evaporation measurements in an empty tank.

as:

$$E = \frac{\gamma}{\Delta + \gamma} \frac{G(z) f(U) (e_{sat} - e_a)}{S_y}$$
(2)

where z is the depth below the surface. Clearly, without any granular medium in place, G(z)=1 and  $S_y=100\%$ .

Using the data shown in Figure 4 with appropriate temperature and humiditydependent corrections and a constant value of f(U) = 22.3, we have determined G (z) for the different granular materials tested. The results of this analysis are shown in Figure 6. The following observations can be made:

- 1. Noting the inherently noisy nature of differentiating discrete data, all materials show a systematic decrease in the evaporation rate with depth. This is in agreement with Figure 4.
- 2. The 80mm basalt is the only material that yields an equivalent evaporation rate systematically less than that of open water.
- 3. A depth of approximately 200mm marks a transition in the behaviour of all other materials. Above this level, the equivalent evaporation rate is systematically higher than that of open water and below this level, the equivalent evaporation rate becomes less than that of open water. This finding is qualitatively consistent with the recent work of Pavia (2008) who observed



**Figure 6** Variation of the function G(z) as a function of depth determined from the data shown in Figure 4 for each granular material type incorporating appropriate corrections for variations in ambient temperature and humidity. Diamonds, sand; downward pointing triangles, 10mm basalt; circles, 80mm sandstone; upward pointing triangles, 80mm basalt. A value of G(z) = 1 indicates an evaporation rate equivalent to open water. The lines indicate fit to the data assuming the form of equation (4): short dashes, sand; longer dashes, 10mm basalt; dash-dot, 80mm sandstone; dash-double dot, 80mm basalt.

similar accelerated evaporation rates from thin layers of wet sand.

4. Normalised evaporation rates of the finer materials (10mm basalt, sand) are systematically higher than those of coarser materials. This is consistent with observations of Hellwig (1973) for sand sizes. However, once the specific yield correction is applied to the 10mm basalt and the sand, the quantity G(z) exhibits only weak dependency on grain size.

### 3.4 Characterising the depth-dependent evaporation rate

Wipplinger (1958) determined that evaporation became zero at a depth of approximately 890mm from the sand surface. This implies a form of G(z) as follows:

$$G(z) = G_{0, lin}(\Lambda - z)/\Lambda; \quad 0 \le z < \Lambda$$
  

$$G(z) = 0; \quad z \ge \Lambda$$
(3)

			Linear model (Eq 3)			Exponential model (Eq 4)		
Material	D <sub>50</sub> (mm)	E <sub>0</sub> (mm/day)	G <sub>0</sub> ,lin	Л (mm)	$r^2$	$G_{0,exp}$	<i>h</i> (mm)	$r^2$
Sydney Sand	0.40	(1)	10.3	254.6	0.97	30.7	61.9	0.96
10mm Basalt	10	(1)	12.1	247.6	0.73	17.8	73.6	0.79
80mm Basalt	80	(1)	0.84	354.7	0.58	0.91	218.1	0.58
80mm Sandstone	80	(1)	2.16	318.3	0.76	2.37	191.0	0.72
Wipplinger				890			672	
(1958) sand							(2)	
Hellwig (1974)	0.32	5.65		770	1.00		398	0.99
Hellwig (1974)	0.47	5.65		680	0.99		281	0.99
Hellwig (1974)	0.53	5.65		673	0.96		270	1.00

**Table 2** Characteristic values for different models of G(z)

Notes: (1)  $E_0$  is dependent on the prevailing environmental conditions, equation (2).

(2) Determined by fitting equation (5) to the first 100 days of the Wipplinger data.

where  $G_0$  is related to the effective evaporation rate at the surface and  $\Lambda$  is the depth at which evaporation is extinguished. The limited reporting of the ambient environmental data by Wipplinger (1958) and Helwig (1974) makes it impossible to determine the quantity  $G_0$ .

An alternative two parameter representation is to assume an exponential decline in evaporation with depth:

$$G(z) = G_{0, exp} e^{-z/h} \tag{4}$$

where evaporation rate reduces by a factor of e over depth h. Note that at relatively small values of z, linear and exponential characterisations are only distinguished by second order terms.

Neglecting the potential radiation-related component and assuming stationary environmental conditions for the Wipplinger and Hellwig experiments, the model forms of equations (2), (3) and (4) have been fitted to their data and the data gathered during this present investigation. The results are summarized in Table 2 and Figure 6. Characterising the data in this manner reveals findings in addition to those summarized in Section 3.3:

- 1. The linear and exponential models are indistinguishable in terms of their characteristic fitting statistics ( $r^2$ , Table 2). However, the linear model predicts and extinction depth  $\Lambda$  of 245.6mm for sand for these present experiments. The data in Figures 4 and 6 show that this is plainly not the case. This suggests that the exponential characterization is better.
- 2. To reformulate Wippinger's data into an exponential form requires integration of equation (4) to obtain an equation of the form:

$$z = h \ln(G_{0, exp}C_1t + 1) \tag{5}$$

where  $C_1$  is a parameter which must be determined by the fitting process. Minimising the square error of a model based on equation (5) using the first 100 days of Wappinger's data yields the value for *h* shown in Table 2.

- 3. The values of  $\Lambda$  and h determined for these present experiments are systematically at least a factor of 2 smaller than the comparable values determined by Hellwig or Wipplinger. The reasons for this difference are not clear at present. This difference may indicate that there are significantly different characteristic depths for two primary terms of the Penman equation when applied to cleared ground conditions. The length characteristic of the radiation-related component would appear to be greater than that characteristic of wind-related processes.
- 4. Comparison of the characterisations of the sand and 10mm basalt experiments of this present study indicate that incorporating the specific yield in equation (2) is an effective manner of capturing the behaviour of finer-grained materials. The characteristic depths are very similar for these two data sets and the exponential fits are very similar in Figure 6.
- 5. Similarly, the fits to the 80mm material also exhibit similar characteristic depths for both models. Further, the estimates of the surface evaporation determined using the two models are remarkably similar. Consequently, the evaporation behaviour of these two materials follows an identical pattern (Figure 6). Only a multiplicative factor is required to differentiate the two materials which is presumably a function of their surface properties.

# 4. Conclusions and Recommendations

An experimental programme investigating wind-forced evaporation rates from large granular materials has been completed. The duration of the present test programme has been substantial as such tests require weeks to months to complete. The results obtained are consistent across the suite of tests but repeat testing of key test conditions is desirable.

It has been found that on a volumetric basis, the evaporation rate from granular media is significantly less than open water below a critical depth which increases with decreasing grain size and increasing rock porosity. The 80mm basalt provided a consistently lower evaporation rate than open water during this study. A systematic increase in the rate of evaporation is observed for sedimentary when compared with igneous rocks of the same size, presumably because of changed rock permeability and surface properties.

This study is able to extend the conclusions of Hellwig (1974) to larger

materials and corroborate his finding that as the grain size increases, the near surface evaporation decreases. This is presumably due to reductions in capillarity and adhesion.

Modifications to Penman's equation for groundwater systems have been developed that perform adequately in terms of the captured data. This study has shown that both linear and exponential parameterisations provide similarly acceptable characterisations of the data. However, the exponential forms do better represent the behaviour of evaporation from sand captured during this study.

There are clear differences in the depth scales required to characterize the variation of evaporation with depth between this present study and those of Wipplinger (1958) and Hellwig (1974). Future work should be able to distinguish more carefully between the radiative and wind-induced components of the total evaporation budget. Present evidence is that radiative processes are able to penetrate deeper into the surface.

These findings are fundamental to further economic assessment and development of hydraulic structures in arid Australia as an adaption approach to changing rainfall and evaporation rates. They may also help provide more robust criteria for design and selection of materials to those countries where sand storage dams are currently implemented.

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