

# Australian Climate Change Adaptation Network for Settlements and Infrastructure

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## Node 4: Infrastructure

### Increasing the adaptive capacity of water storage systems by reducing evaporation

In many arid countries, the annual evaporation rate is capable of exceeding the annual average rainfall. This means that water storage is not sustainable, having the potential to severely impact communities and industries who suffer from water scarcity. Future impacts of climate change, including intensification of rainfall events and increasingly prolonged periods of drought, are likely to exacerbate these issues. With rainfall patterns becoming less predictable, it is important to build the adaptive capacity of water storage systems. One means of improving adaptive capacity is to reduce evaporative losses.

Conventional open water reservoirs are highly vulnerable to evaporative loss. In Africa, artificial sand-filled dams have been used to reduce evaporation for many decades (Wipplinger, Nilsson). These 'groundwater dams' reduce evaporation by reducing the surface area of water exposed to the atmosphere, storing water within soil pores. They may be developed and used as an effective adaptation approach to changing rainfall and evaporation rates. Research is currently being conducted to determine the feasibility of replacing open water dams with groundwater dams (Bennett et al. 2008), and to investigate improvements in the design of groundwater dams (Peirson et al. 2010; Busutill et al. 2011) in order to reduce evaporation rates and help communities adapt to changes in climate which threaten their water supplies.

Bennett et al. (2008) compares the storage efficiency of farm dams (using data taken from a number of sites in NSW from 1996 to 2006) to computed evaporation and storage efficiency from equivalent dams filled with coarse material. Evaporation from the groundwater dams is found to decrease as a function of water depth below the surface of the soil, until, at a depth of approximately 0.9m, evaporation is negligible. The study reveals that the use of groundwater dams has the potential to provide more reliable water supplies and reduce runoff diversion from downstream catchments. It is concluded that groundwater dams appear to be an effective storage solution, especially in arid areas for larger, deeper storages, but more detailed simulations over longer climatic periods as well as field trials should be undertaken before they are implemented as an adaptation approach.

A systematic suite of investigations into the role of grain size in wind-forced evaporation from groundwater storages was conducted by Pierson et al. (2010). The test facility comprised a timber 0.9m wide by 0.6m high wind tunnel, with air drawn through the tunnel by a large fan. The storage materials tested included both igneous and sedimentary rock spanning nominal sizes from 0.4mm to 80mm. On a volumetric basis, the evaporation rate was found to be significantly less than that of open water for groundwater systems below a critical depth. The tests performed were 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 effect was presumed to be due to reductions in capillarity and adhesion with increasing grain size. A difference in surface texture of the materials used was also shown to have a significant effect on the evaporation rate.

The study revealed clear differences in the depth scales required to characterize the variation of evaporation with depth compared with those of Wiplinger (1958) and Hellwig (1974). This is likely due to the fact that radiative evaporative processes are able to penetrate deeper into the water surface, calling for further investigations to be performed in order to distinguish more carefully between the radiative and wind-induced components of the total evaporation budget.

Busutill et al. (2011) conducted experiments using the same apparatus to test the effects of differences in surface texture of materials in reducing evaporation. To investigate these effects, experiments were performed by covering the surface of the water with three types of floating modular devices, each having three different surface characteristics. It was recognised that surface adhesion and capillarity processes may significantly enhance the wetting of the skin of these units, thereby reducing their effectiveness in preventing evaporation. Specifically, floating devices with hydrophilic surfaces tended to cause water to be drawn across their skin, actually *increasing* the surface area of water exposed to evaporative processes.

The testing of devices with porous surfaces revealed that, although the presence of the devices reduces the exposure of the water surface to evaporative effects, the actual evaporation rate can be higher than that which in the absence of the devices. Consequently, surface texture can be seen as important in determining evaporation rates. Devices with clean surfaces were shown to reduce wind-forced evaporation rates by approximately 65%. Assessment of the potential role of surface biological growth in reducing this effectiveness indicated that slimes do not significantly compromise the performance of such devices.

These studies are fundamental to further development of hydraulic structures in arid regions 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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# Fill in the Dams?

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**Abstract:** Small dams in inland Australia are key farm infrastructure and are essential for the economic survival of rural business during sustained drought. However, harsh arid climatic conditions result in annual evaporation losses greater than annual water usage. The purpose of this study is to investigate the feasibility of replacing small farm dams with groundwater dams, constructed by filling the farm dams with gravel or sand. Water is then stored in the soil pore space, where evaporation decreases as a function of water depth below the surface of the soil, until at a depth of 0.9m, evaporation is negligible. Although storage volume is reduced, this method may be an efficient alternative to the current unavoidable evaporation losses from open surface waters. Daily evaporation data, and storage efficiency of representative farm dams has been compared to the computed evaporation and storage efficiency from equivalent dams filled with coarse material. Data has been taken for a number of sites in western New South Wales from 1966 to 2006. Results have shown that when the water level is below the surface, evaporation is significantly reduced and water saved, particularly from larger dams in arid regions rather than semi-arid regions. For the case of the largest farm dam considered at Mildura, the average annual volume of water available in the farm dam over the 40 years of data is 65 percent. Results for the corresponding groundwater dam give the average annual available volume calculated as 24 percent of the total dam volume (i.e. 61 percent of the porosity). The study concludes that the application of groundwater dams would be beneficial in arid areas of Australia for larger, deeper storages, however not much benefit is seen in their application in semi-arid regions. Groundwater dams reduce evaporation losses and appear to be an effective storage solution but more detailed simulations over longer climatic periods as well as field trials should be undertaken before they are implemented in Australia.

**Keywords:** Groundwater dams, evaporation loss, small farm dams, Australia, arid, semi-arid.

## 1. INTRODUCTION

Unpredictable and low rainfall brings great risk of economic survival to farmers in arid and semi-arid areas of Australia who depend on crop and cattle production as a primary source of income. Traditional water storage dams experience sizeable evaporation losses. Prolonged periods of drought in arid and semi-arid regions are severely affecting communities who regularly suffer from water scarcity. Inland Australia does not have the regular rainfall patterns of the coastal regions and the large dams supplying the coastal populations do not provide sustainable storage for the rural population. Due to the current issues associated with drought and increasingly low storage levels across the nation, Australia is looking for more sustainable methods of storing and conserving water in these regions.

This not a new problem. Weeks stated almost 25 years ago, “considering the importance of evaporation in the water balance of reservoirs, it is surprising that so few detailed research projects have studied the problem” (Weeks, 1983, quoted in Watts, 2005). The development of Australia is limited by its water resources and our limited understanding of how to manage them in a sustainable manner.

Internationally, groundwater dams are used to dam small ephemeral rivers and streams in order to intentionally cause sedimentation. Water is then stored in the soil pore space, where evaporation decreases as a function of water depth below the surface of the soil. At a depth of approximately 0.9m (Wipplinger 1958), evaporation becomes negligible. Groundwater dams could potentially be used in Australia to reduce the risks associated with crop failure and livestock starvation, malnutrition and death during long drought periods by providing emergency supplies during intense drought.

This contribution considers whether groundwater dams may be a practical and efficient way of storing water in arid and semi-arid climates of inland Australia. As a preliminary investigation of potential Australian application, the concept of filling in existing farm dams with coarse granular sediments is considered. Such a change will inevitably incur greater initial set up costs which may be offset by economic benefit of the amount of water saved from evaporation. A primary cost will be filling in the dam with an appropriate material with high specific yield.

Multitudes of small farm dams exist in arid inland Australia and Manning (1987) states that “small reservoirs have proportionately higher evaporation losses” [than large reservoirs]. Research by the National Program for Sustainable Irrigation shows that depending on surface area and depth, “40 percent of stored water in farm dams can be lost through evaporation”. Any alternative storage scheme must be more reliable in terms of both the net supply volume of the supply and suitable quality (White, 1960; Van Haveren, 2004, Nissen-Petersen, 2006). Alternative preventative measures to reduce evaporation losses in Australia involve the use of chemical films, covers, sun shades and tree barriers (NPSI, 2005; Manning, 1987) and there are significant and multiple difficulties in their application to small farm dams in arid and semi-arid Australia.

## 2. GROUNDWATER DAMS

A conventional groundwater dam “obstructs the flow of groundwater and stores water below the ground surface” (Nilsson, 1988; VSF-Belgium 2006). This term refers to both sand storage dams and subsurface dams. A subsurface dam “is constructed below ground level and arrests the flow in a natural aquifer, whereas a sand storage dam impounds water in sediments caused to accumulate by the dam itself” thereby creating an artificial aquifer (Nilsson, 1988). A conventional sand storage dam is shown in Figure 1.

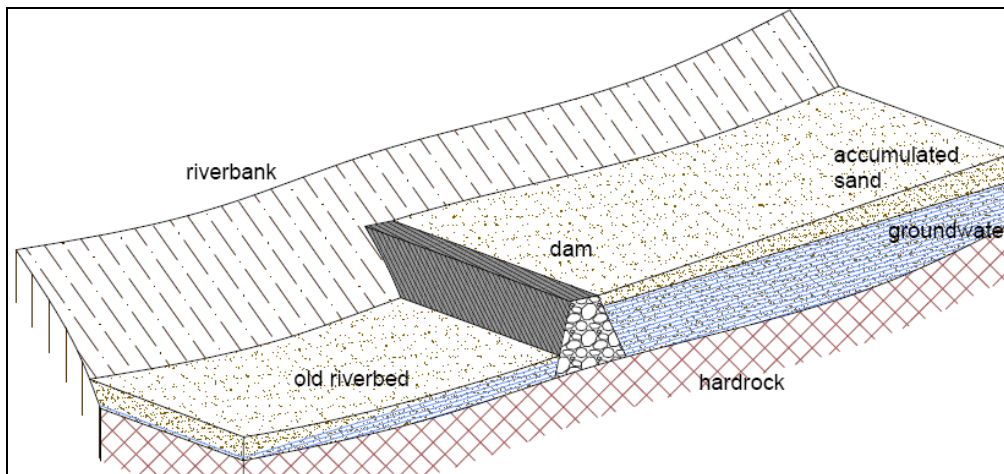


Figure 1 - Conventional Sand Storage Dam (from Borst 2006)

In order to construct a sand storage dam in a river bed, the dam wall must be built up from the dry river bed in stages, each no more than thirty centimetres high (Nissen-Petersen, 2006). The river flows and coarse grained materials such as sand and gravel are deposited behind the dam wall during flood events (Ward and Robinson, 2000). These small incremental wall heights, documented in the construction of sand storage dams in Kenya, Namibia and India allow suspended silty materials to wash out and pass by, promoting preferential retention of the coarser sediments of higher yield (Wipplinger 1958; Argarwal et al, 1991), since silty materials will reduce the permeability, specific yield and rate of recharge of the dam (Nilsson, 1988).

Specific yield is a measure of how much water will be extractable from the groundwater dam. Whilst a fine grained soil and a coarse grained soil may have the same porosity, the size of the pores will be much smaller in the fine grained soil and most of the water will be inaccessible capillary water (Manning, 1987). A coarse grained soil will have a much higher permeability and therefore a superior specific yield from the extractable gravity water. The specific yield of the storage is the amount of water that drains freely from a unit cross-sectional area when the water level falls by one unit (Acworth, 2007). The specific yield is expressed as a percentage of the total volume. Literature values for sediments composed of medium sands and larger material will have specific yields between 20 and 30 percent, falling rapidly once the representative grain diameter is less than 0.2mm.

### 3. MODELLING OF CONVENTIONAL AND GROUNDWATER DAM PERFORMANCE

During this investigation, the performance of conventional and groundwater farm dams was investigated for six sites in western New South Wales using available data in conjunction with a simple rainfall-runoff model of storage.

Rainfall runoff from the upstream catchment ( $V_{runoff}$ ) is assumed to be the sole inflow to the storages. Outflows are farm demand ( $D$ ), evaporation ( $E$ ), seepage losses and any dam overflow of excess capacity ( $V_{overflow}$ ). It has been assumed that any losses due to seepage are negligible. As daily records were the most suitable data, a daily time step has been used in the model. The equation for the volume of stored water  $V$  on day  $i$  is:

$$V_{(i)} = V_{(i-1)} + V_{runoff(i)} - D - E_{(i)} - V_{overflow(i)} \quad (1)$$

It should be noted that the surface area of each farm dam is on average 0.5 percent of the area of the catchment and so the direct rainfall onto the storage was considered negligible. If the direct rainfall on the storage was included the effect would be as if the annual evaporation has reduced by the annual rainfall. A spreadsheet model was created for the purpose of comparing the available volume of water in the farm dam and the same sized groundwater dam on a daily time step over the period of available rainfall and evaporation data.

#### 3.1 Rainfall and Evaporation Data

Approximately forty years of daily rainfall and pan evaporation data was available at the six sites selected. The sites and the duration of their recorded observations are summarised in Table 1 and mean values are summarised in Figure 2. In the context of much longer climatic records in eastern Australia, it is to be noted that the period 1967 to date is regarded as a period of above average rainfall (Rančić and Acworth, 2008).

Table 1. Site Details

Site	Record Length (years)	From	To
Mildura	39	01/01/1967	31/12/2006
Cobar	39	01/01/1969	20/07/2007
Menindee	27	25/02/1968 to 31/12/1985 & then 01/01/1996 to 31/12/2006	
Wagga Wagga	39	01/12/1966	31/12/2006
Bathurst	33	01/12/1972	31/12/2006
Canberra	39	01/01/1967	31/12/2006

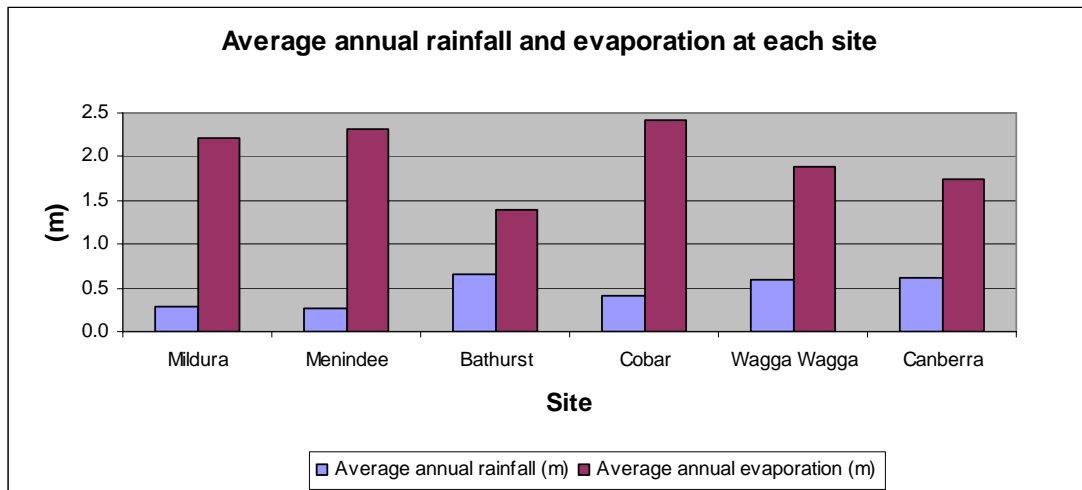


Figure 2 - Summary of Average Annual Rainfall and Evaporation at Each Site (Bennett, 2007)

Evaporation from groundwater storages depends on the water level below the surface, which also has a correlation with grain size and material permeability, which both affect evaporation. Nilsson (1988) presents a study by Hellwig (1973) in Namibia where the average daily evaporation was calculated against the depth of the water table below the

sand surface for three different soil mixtures. These soil mixtures were fine, medium and coarse grained sand. Hellwig's results show that evaporation decreases with increasing grain size when the water table is below the surface level. When the water table is at the surface it appears that grain size has no effect on the rate of evaporation. It can also be seen that as the water table decreases below the surface, the rate of evaporation decreases for all grain sizes, but most significantly for coarse grained soils. During this investigation, it has been assumed that evaporation rate decreases linearly from the pan evaporation value at the surface to zero once the water surface is deeper than 0.9m from the surface.

### 3.2 Farm Dam Characteristics

Using Neal *et al.* (2001) supplemented with an aerial photographic survey of farm dams for each site using imagery available from Google Earth (2007), representative farm dam sizes of 1ML, 3.5ML and 9ML at each site were determined.

In each case, the storage was assumed to be a truncated pyramid with base areas determined from the aerial photography and side slopes of 1V:1.5H. Total storage depth was determined from the corresponding volume.

### 3.3 Groundwater Dam Sediment

It was assumed that any infill sediment material was used to fill the dam with moderate compaction due to dump placement during construction. A uniform porosity of 39 percent and a specific yield of 27 percent, typical of a coarse sand (Todd, 1980), has been assumed.

### 3.4 Runoff

For the arid and semi-arid regions of Australia, flow records for small catchments are virtually non-existent, consequently, we must estimate the probable runoff that the dam will receive (Nelson, 1997). Runoff as a proportion of rainfall depends on the catchment characteristics such as vegetation, land use, climate, catchment size, topography and the local geology.

The size of representative catchments in each location was determined from the aerial photographic survey. A total of 10 dams were selected in the vicinity of each location of the study and their dimensions recorded and the surrounding terrain noted to obtain an approximate value of the catchment area. The average catchment area calculated for each location as shown in Table 2 has been used in the model.

Table 2. Representative Catchment Surface Area

Site	Catchment surface area (km <sup>2</sup> )
Mildura	0.30
Cobar	1.60
Menindee	0.75
Wagga Wagga	0.17
Bathurst	0.33
Canberra	0.40

The volume of runoff has been calculated by the Rational Method using a daily time step. A runoff coefficient of 0.17 was selected from Table 5.5 in Ward and Trimble (2003) as appropriate for these conditions. Whilst this estimation of the runoff coefficient is less than ideal, little can be done about the vast lack of information in ungauged catchments. It is however noted that any future work regarding this study justifies the use of a more sophisticated runoff model.

### 3.5 Demand Calculation

Demand is best calculated from survey. Patterson (1985, cited by Gould *et al.*, 1999) found from a survey of rural domestic water use reliant on rainwater supplies in New South Wales that an average daily water demand was between 126 to 165 litres/person/day. A maximum of 350L/person/day was recorded. Based on this statistic for the purpose of the computer analysis a daily household water demand of 220L/person/day was adopted.

Detailed analysis of household size and stock populations were impossible during this investigation. Consequently, it was assumed that the daily demand from the farm dams were constant flows of 2.7m<sup>3</sup>/day, 8.6m<sup>3</sup>/day and 18.6m<sup>3</sup>/day based on information from Neal *et al.* (2001) according to the reservoir capacity.

We are assuming that small farm dams are not used for crop irrigation. Therefore demand has been assumed to be approximately constant all year round, however a sensitivity analysis of the model with respect to the demands and runoff is recommended for incorporation in any future investigation.

#### 4. RESULTS

For each model scenario, inflow and outflow volumes and mean storage water levels were calculated on a daily basis over a period of record of approximately 40 years. Annual evaporation for the three different sized dams at the six locations modelled is shown in Figure 3. A representative set of results for the case of a 9ML dam at Mildura is given in Table 3 and shown in Figure 4. It can be seen that the average annual volume of water available in the farm dam over the 40 years of data is 65 percent of maximum capacity. Results for the corresponding groundwater dam appear to be somewhat in the range expected with the average annual available volume calculated as 24 percent of the total dam volume (i.e. 61 percent of the porosity). Figure 4 shows the overall trends for each location include the fact that the volume change in the groundwater dam as a proportion of the total volume is more variable than in a comparable farm dam. This is because there is less net total volume available for water storage in a groundwater dam of the same size and the demand remains the same.

However, it can also be observed that in spite of the smaller net storage volume in the groundwater dam (39 percent of the conventional structure), the frequency of events of zero capacity are comparable between the two storages. The diversion of runoff from the downstream receiving waters is significantly reduced for a groundwater dam. By implication, any increase in groundwater dam capacity will support higher farm demand with lower net diversion of flow from the downstream catchments. The number of days of zero capacity is considerably less at only 90 days over 39 years compared to 144 days of failure for the farm dam. Recharge occurs much faster in the groundwater dam as small runoff events are protected from evaporation during dry periods.

Table 3. Summary of Results for 9ML Dam (Case 3) at Mildura

	Ave annual rainfall (m)	Ave annual Evaporation (m)	Ave Annual Available Volume (ML)	Volume Runoff (ML)	No. days of failure (Vol < demand)
<b>Farm Dam</b>	0.286	2.216	5.89	95	144
<b>GWD</b>		0.426	2.12	274	90

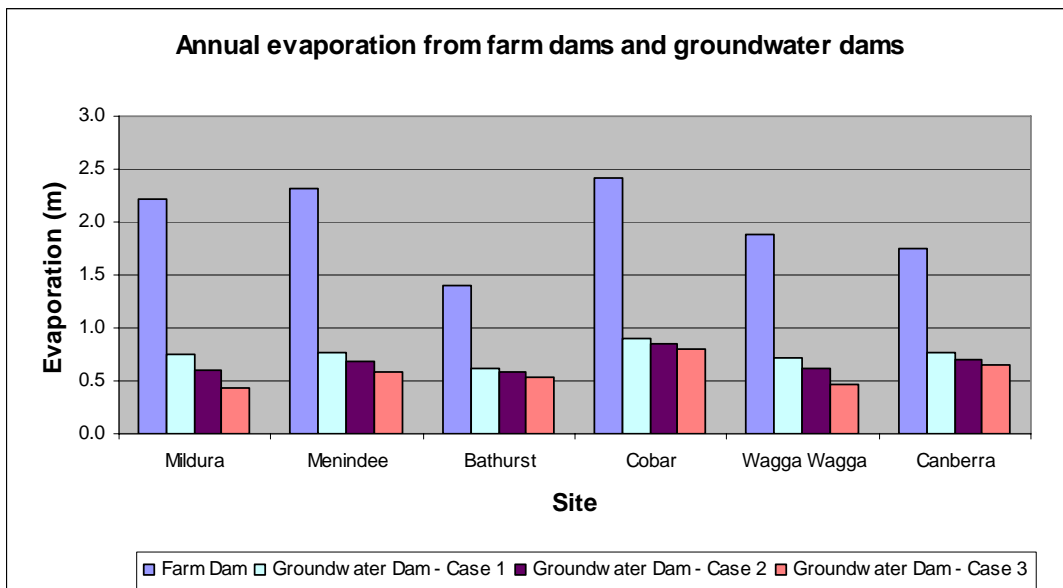


Figure 3 - Summary of Annual Evaporation From Conventional and Groundwater Dams (Bennett, 2007)



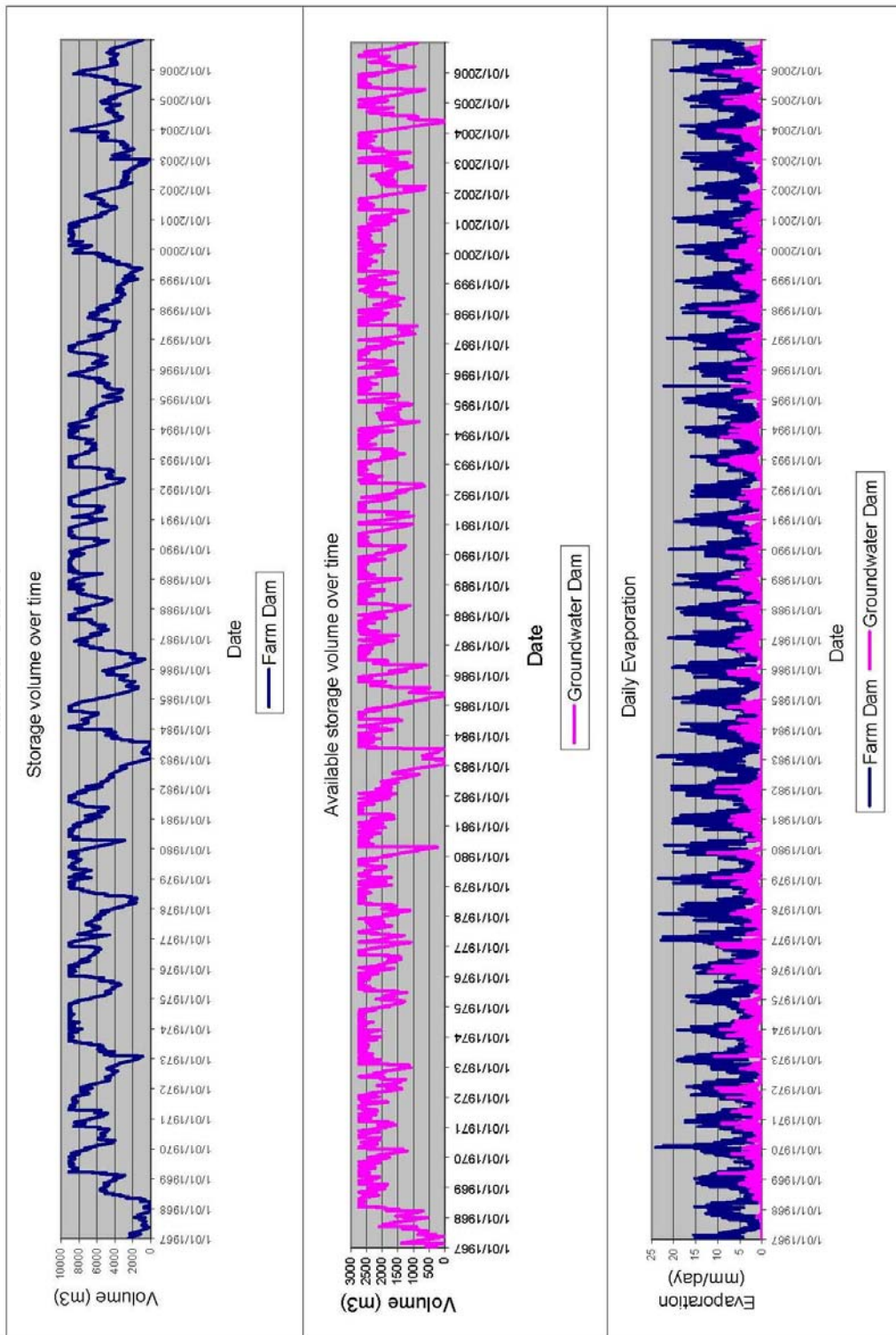


Figure 4 - Results for Case 3 at Mildura (Bennett, 2007)

#### **4.1 Construction and Economic Feasibility**

From a construction feasibility point of view, if all basic requirements such as appropriate material and required plant are available locally, then construction is believed to be straightforward. Construction time will be largely based on the time required for bulk earthworks, which depends on the volume of the dam and the haulage distance of materials. If constructed on an appropriate site, and built properly, it is generally concluded that groundwater dams will be successful as they have been in other parts of the world (Nilsson, 1988). The addition of sediment to the dam storage may compromise geotechnical considerations which may require additional earth mass.

Regarding economic feasibility, if material is readily available at little or no cost, then the main cost of this exercise is attributed to the hire of construction equipment as well as well and pump purchase and installation costs, or the costs of a gravity draining pipe from which water can freely flow. Economic feasibility will also be relative to the available storage volume and water saved from evaporation.

### **5. CONCLUSIONS AND RECOMMENDATIONS**

Whilst these results must be regarded as preliminary, the use of groundwater dams has significant potential to substantially reduce evaporation from farm dams in arid and semi-arid Australia. This has the potential to produce two desirable outcomes for agricultural management in inland Australia:

1. provide more reliable water supplies; and,
2. reduce runoff diversion from downstream catchments.

However, this investigation has used literature data values to assess the effectiveness of groundwater dams including sediment specific yield, catchment runoff coefficients and evaporation rates in shallow groundwaters. Further desktop investigation of groundwater dam potential using more sophisticated seasonal demand models may be justified. Nonetheless, field trials will be necessary to demonstrate the potential of these structures under Australian conditions.

A further possibility is to consider the use of groundwater dams underlying more conventional storages. This may have the desirable characteristic of maintaining a large active storage volume yet also providing water supply protection during times of extreme drought.

The study concludes that the application of groundwater dams would be beneficial in arid areas of Australia for larger, deeper storages, however not much benefit is seen in their application in semi-arid regions. Groundwater dams reduce evaporation losses and appear to be an effective storage solution but more detailed simulations over longer climatic periods as well as field trials should be undertaken before they are implemented in Australia.

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## 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 0.4mm 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 poorly-graded 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, 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.

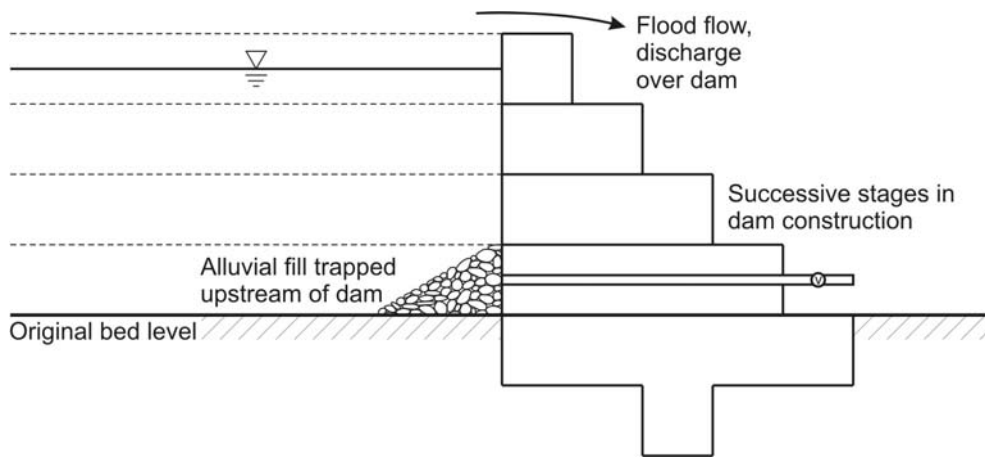


Figure 1. Conceptual diagram of a sand storage dam.

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 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.

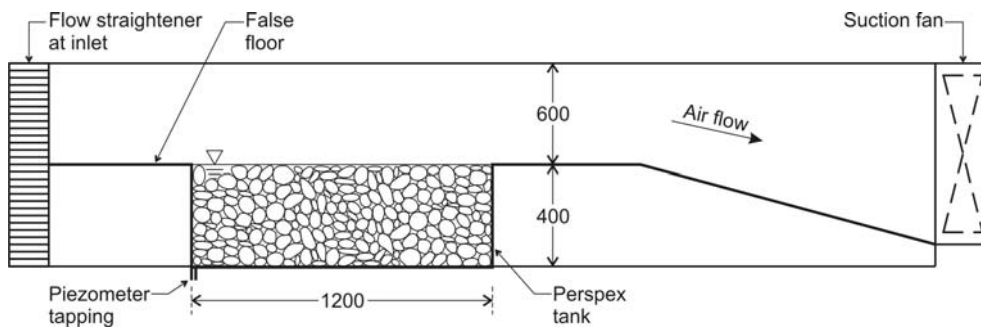


Figure 2. Side view of the test facility

### 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.

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

Material	$D_{50}$ 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 to 2.0)	46	17	29	13.5-23.6	35-93
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

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 ~7% of the total volume.



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



### 2.3 Test procedures

Each test material was installed within the test facility and fully saturated. A constant wind of  $6.9 \pm 0.2 \text{ms}^{-1}$  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.

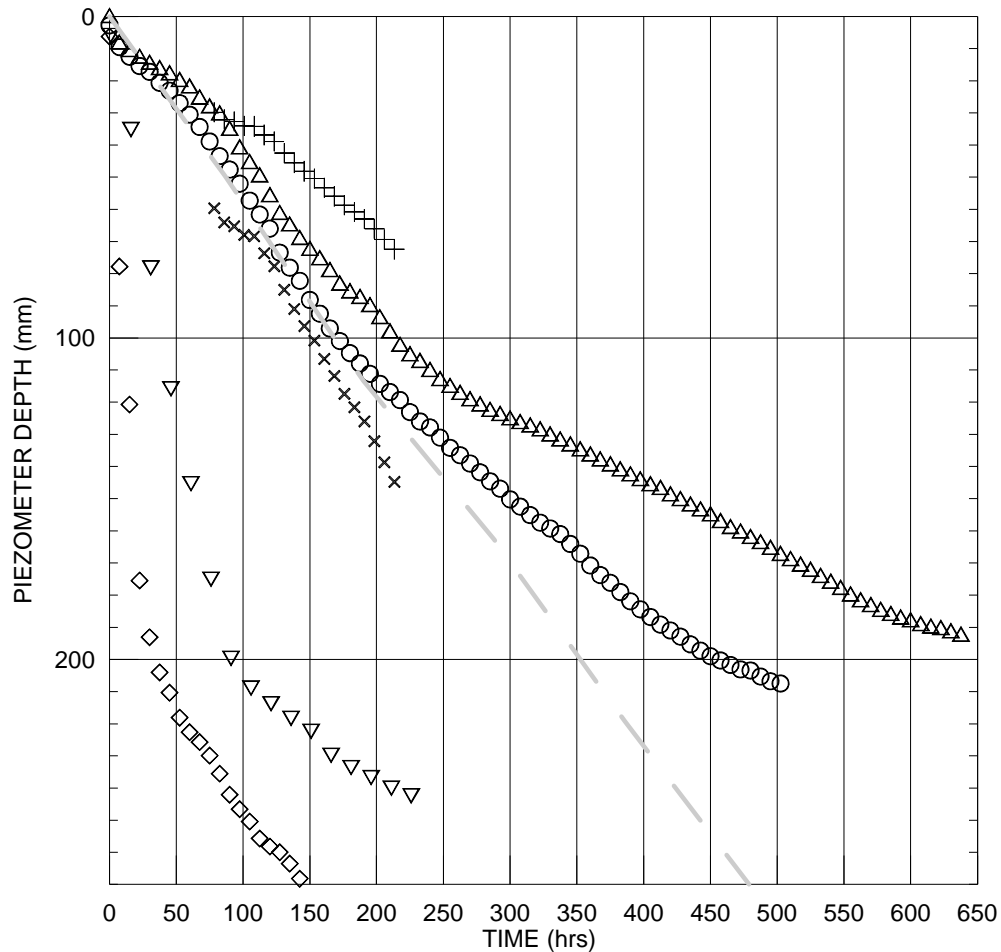


Figure 4. Depth indicated by the piezometer as a function of time for the different test materials: pluses, open water; diamonds, sand; downward pointing triangles, 10mm basalt; circles, 80mm sandstone; upward pointing triangles, 80mm basalt. The grey dashed line shows the Wipplinger (1958) data at the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

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.

### 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.
2. 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 Wiplinger (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):

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

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 ( $E_v=S_y E$ ) in finer grainer materials. However, increased capillarity-related effects in finer grained materials would be expected to increase  $E_v$ . 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) as:

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

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

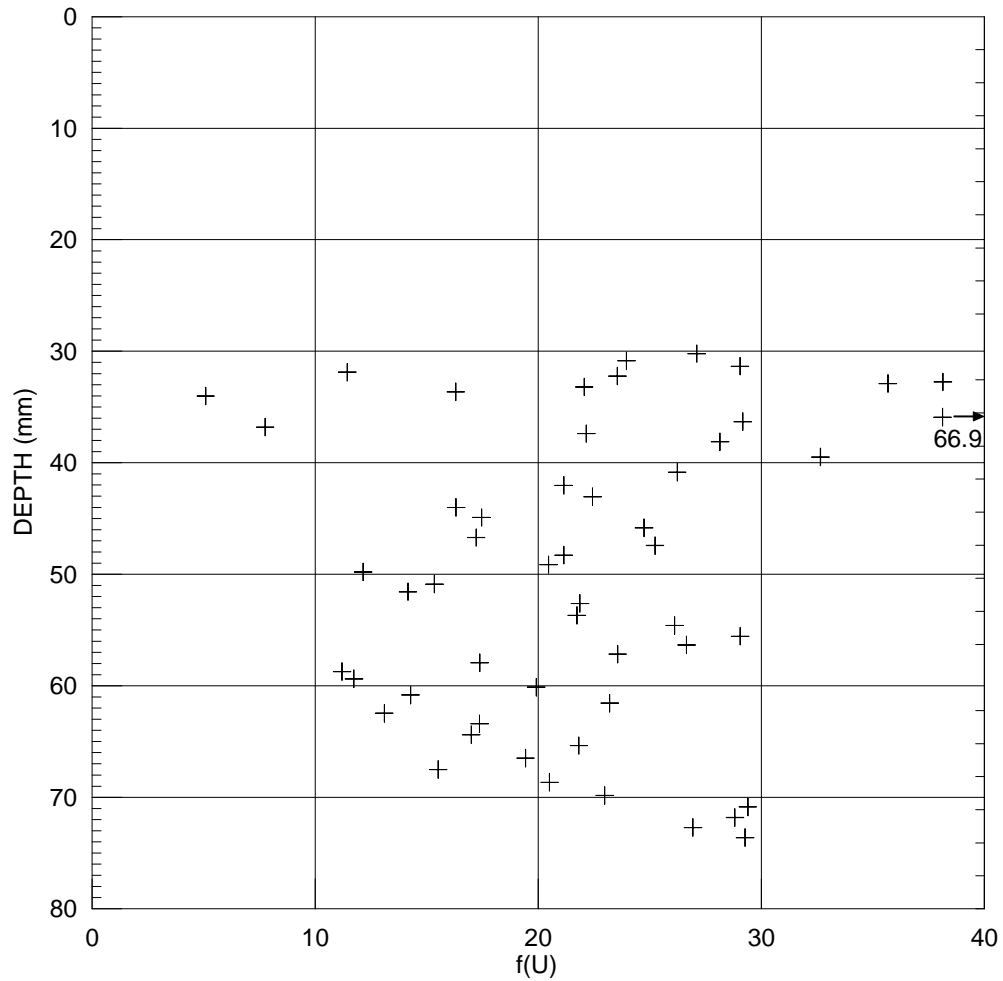


Figure 5. Variation of the function  $f(U)$  determined from the evaporation measurements in an empty tank.

Using the data shown in Figure 4 with appropriate temperature and humidity-dependent 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.

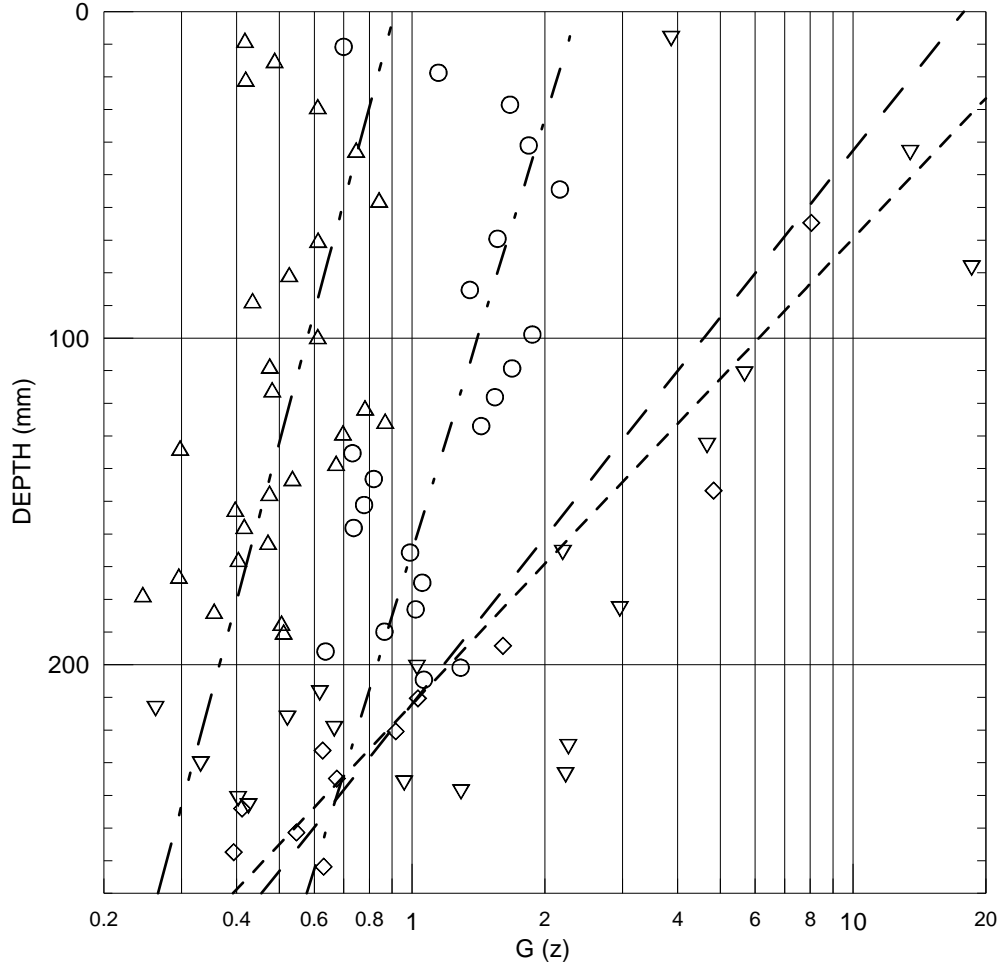


Figure 6. Variation of the function  $G(z)$  as a function of depth determined from the data shown in Figure 4 for each granular material type incorporating appropriate corrections for variations in ambient temperature and humidity. Diamonds, sand; downward pointing triangles, 10mm basalt; circles, 80mm 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.

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 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

Wiplinger (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:

$$\begin{aligned} G(z) &= G_{0,lin} (\Lambda - z)/\Lambda; & 0 \leq z < \Lambda \\ G(z) &= 0; & z \geq \Lambda \end{aligned} \quad (3)$$

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 Wiplinger (1958) and Hellwig (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:

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

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.

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

Material	$D_{50}$ (mm)	$E_0$ (mm/day)	Linear model (Eq 3)			Exponential model (Eq 4)		
			$G_{0,lin}$	$\Lambda$ (mm)	$r^2$	$G_{0,exp}$	$h$ (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
Wiplinger (1958) sand				890			672 (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

**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 Wiplinger data.

Neglecting the potential radiation-related component and assuming stationary environmental conditions for the Wiplinger 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 an 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 Wiplinger's data into an exponential form requires integration of equation (4) to obtain an equation of the form:

$$z = h \ln(G_{0,exp} C_1 t + 1) \quad (5)$$

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 Wiplinger. 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 Wiplinger (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.

## 5. Acknowledgements

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# Laboratory assessment of the performance of porous coverings in evaporation mitigation

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**Abstract:** Loss of water resources due to evaporation is an issue of ongoing concern in Australia with lots of evaporation mitigation devices, such as floating modular devices, being evaluated for use. This paper describes a preliminary evaluation of the effectiveness and efficiency of floating modular devices with various surface materials and therefore different magnitudes of adhesion between these devices and water. Floating modular devices work by decreasing the surface area of water available for evaporation to occur. However some materials with high adhesion to water, will draw up the water onto itself, whereas other materials are not easily wetted and will repel water.

The evaporation experiments performed included an open water control test, and three floating modular device tests. The three devices were tennis balls; which represent hydrophilic materials, smooth polyethylene balls; which represent hydrophobic materials, and smooth polyethylene balls with a slime-mould growth; which represent hydrophilic materials which have aged and acquired a biological surface growth.

Analysis of the test results showed that floating tennis balls actually increased the amount of evaporation by a factor of 1.33, whereas both the clean and slime-mould coated polyethylene balls reduced the rate of evaporation by about 65%. It was possible to quantify an adhesion coefficient to account for the increase in evaporation with respect to the planar surface area of water. These factors were 4.5, 2.1 and 2.0 for the tennis ball, smooth polyethylene ball and slime-mould coated polyethylene ball tests respectively. This means that the impact of adhesion is great as the evaporation rate in terms of planar surface area of water was always increased.

**Keywords:** Evaporation, farm dams, surface sheltering, adhesion, capillarity.

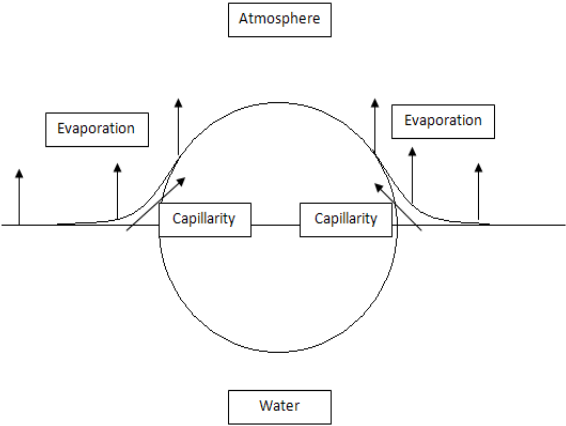
## 1. INTRODUCTION

Better management of water resources is becoming increasingly important as water usage continues to grow internationally. Existing water supplies may also be vulnerable to climate change effects. Water resources are especially important in Australia which has a predominantly arid climate with average annual rainfall of less than six hundred millimetres over eighty per cent of the continent and average annual rainfall over half the continent less than three hundred millimetres (Bureau of Meteorology, 2010). Further, data collected by the Bureau of Meteorology over the past three decades shows that average annual pan evaporation over the vast majority of Australia exceeds one metre (Bureau of Meteorology, 2010). This disparity between annual rainfall and evaporation highlights the importance of minimising evaporation within Australian water supply systems – particularly in inland Australia.

Preliminary assessment by Bennett and Peirson (2007) showed that the use of groundwater dams (artificial aquifers with the water stored within the grain pores) have three major potential benefits over their conventional open water counterparts. First, groundwater dams provide more reliable water supplies than conventional farm dams in arid inland Australia. Secondly, water diversions from downstream water bodies are significantly reduced. Thirdly, net evaporation, and therefore overall water loss, is significantly reduced. A recent laboratory study by Peirson *et al.* (2011) has quantified the increase in specific yield and the reduction in wind-forced evaporation with increasing grain size for sands and rocks up to 80mm diameter.



An alternative and potentially economically feasible method of evaporation reduction is the reduction in surface area of water by the addition of floating modular devices to the surface of reservoirs. In recent years, many modular devices have been developed commercially to reduce the evaporation from an open water body by reducing the surface area of water exposed to the atmosphere. Floating modular devices may also potentially reduce evaporation by modifying the air velocity and humidity immediately above the water surface (e.g. NPSI, 2006).



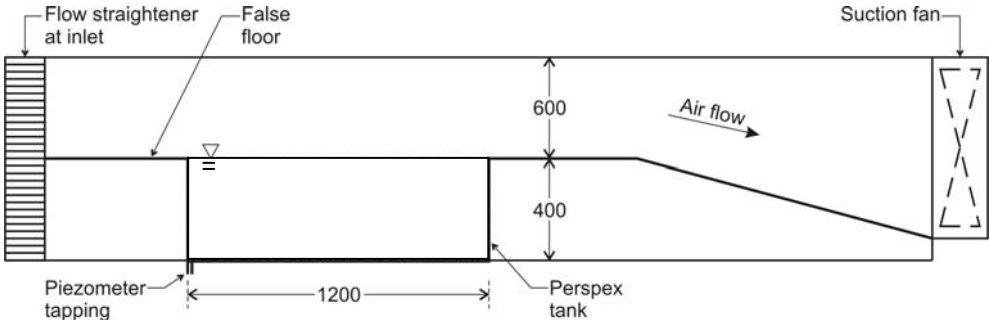
**Figure 1. Conceptual diagram showing adhesion and capillary processes on an isolated floating modular device**

However, there is also the possibility that adhesion and other capillarity-related processes may significantly enhance wetting of the skin of the devices thereby reducing the efficiency and effectiveness of these devices. Specifically, as depicted in Figure 1 below, if the surface of the floating modular device is hydrophilic, the water will be drawn across the skin of the modular device expanding the surface area of water exposed to evaporative processes.

Hellwig (1973), Pavia (2008) and Peirson *et al.* (2010) have all noted significantly enhanced evaporation rates for near-saturated granular materials, presumably due to adhesive processes drawing water to and across the surfaces of the grains (Figure 1).

Evaporation may also be enhanced following rain or dew deposition, or by wetting or spray generation by wind-induced rolling of a surface piercing modular device.

This present contribution is a preliminary laboratory assessment of the potential for adhesive processes to reduce the effectiveness of floating devices in reducing evaporation from open water bodies. In the following sections we describe the techniques used during the investigation, summarize the results obtained and make recommendations for future investigations. (See Busuttill, 2010.)

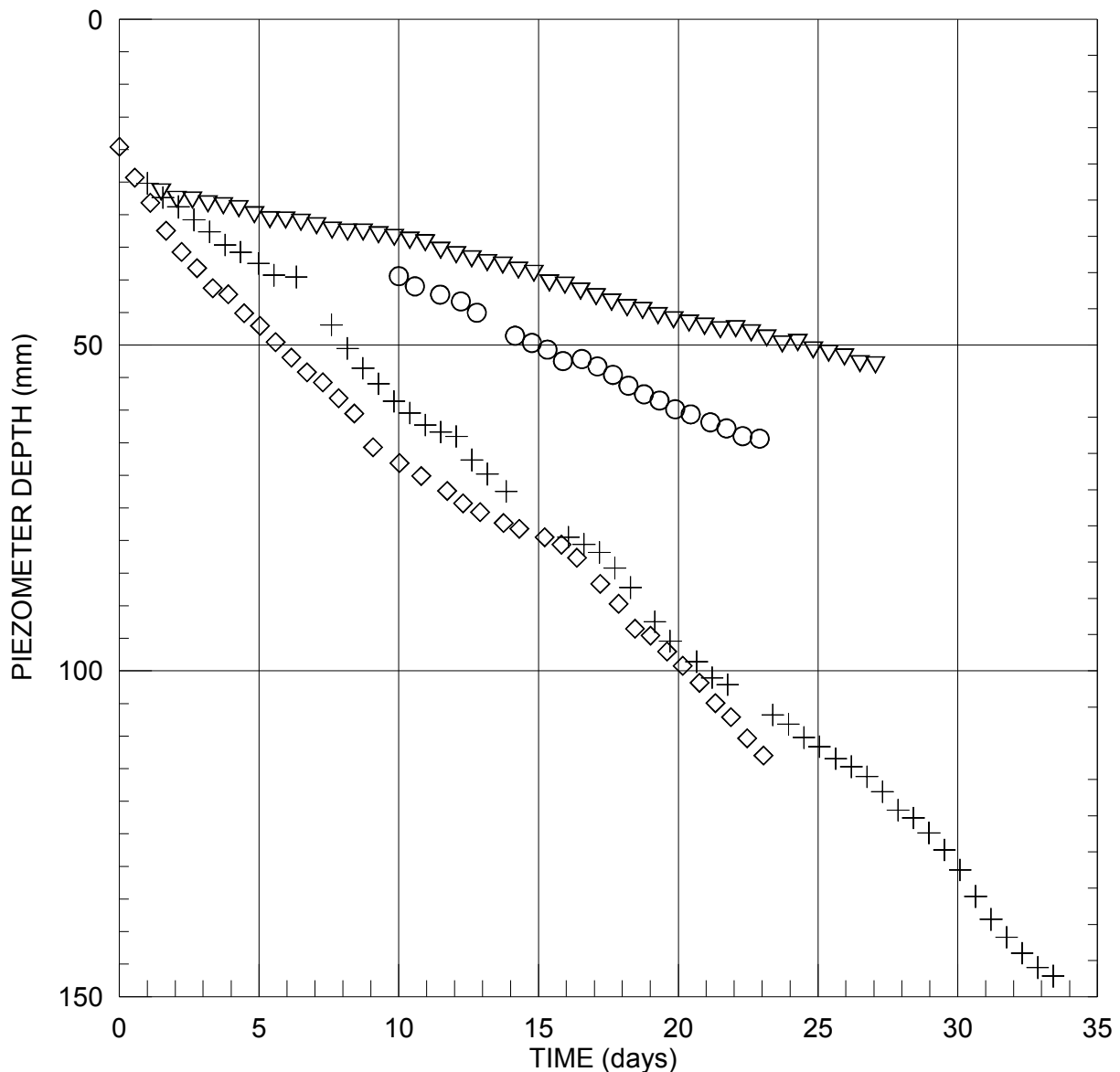


**Figure 2. Side view of the test facility**

## 2. METHODOLOGY

### 2.1. Test facility

The test facility is identical to that used by Peirson *et al.* (2011) to quantify wind-forced evaporation from groundwater dams and is shown diagrammatically in Figure 2. It is located within the 1.0m by 0.6m wind tunnel at the Water Research Laboratory and consists of a Perspex tank 1.2m by 0.3m and 0.4m deep encased in the floor of the tunnel. A suction fan draws air at a constant velocity of  $6.9 \pm 0.2$  m/s through the tunnel. Flow straighteners at the tunnel inlet ensure that the air flow transitions smoothly into the tunnel.



**Figure 3. Recorded water level variation with time for the duration of each test: +, open water; diamonds, tennis balls; triangles, clean polyethylene balls; circles, slime covered polyethylene balls.**

Water levels are monitored via a piezometer connected to the water tank. The piezometer is fitted with a *Franklin* automatic water monitoring system that continuously transmits water levels with an accuracy of 0.1mm to a nearby computer fitted with appropriate analogue to digital conversion hardware. Air temperature and relative humidity were monitored using a probe inserted through the

roof of the wind tunnel and these data were used to correct evaporation data derived from the recorded water level changes. All water level, humidity and air temperature data was recorded by the computer every 2 minutes.

A test was undertaken with no floating modules to provide a reference for subsequent testing with floating modular devices.

## 2.2. Floating Modules

In spite of the relatively large size of the test facility, it remained infeasible to test appropriately full size modular devices. Consequently, to investigate the impact of adhesion on the rate of evaporation, modular devices with three different surface characteristics were used to cover the surface of water within the test rig and an evaporation test was performed on each.

Floating tennis balls were used to represent a case in which the material skin would actively draw water up onto their surfaces.

To represent more hydrophobic devices, smooth plastic balls made of low density polyethylene were used. It was observed that wetting of the ball skins caused water droplets to form rather than spreading out over the entire surface of the balls.

To simulate biological growth on the surface of initially smooth devices, the biological organism *Physarum polycephalum* or slime-mould was selected to grow on the smooth polyethylene balls because of its vigorous growth and minimal health risk (Southern biological, 2009). A potentially significant and interesting feature of *Physarum polycephalum* is that the mould has bright yellow "veins" which mobilise and distribute fluid within the colony - behaviour known as is cytoplasmic streaming. This could potentially enhance adhesive processes that transport water onto the wind-exposed surfaces of the modular device and increase the effective surface area from which evaporation could occur.

Each of these characteristic modules was tested in turn within the facility. It should be noted that none of the balls tested were observed to spin or shift position. The buoyancy of both the tennis balls and polyethylene balls was set by water injection to ensure that they floated semi-immersed.

**Table 1. Summary of test characteristics, conditions and key results.**

	Open Water	Tennis Balls	Clean Polyethylene Balls	Polyethylene Balls with slime
Module diameter (mm)	-	63	52	52
Number of modules	0	84	144	144
Exposed water area (m <sup>2</sup> )	0.3704	0.1085	0.0646	0.0646
Propn. of tank area exposed (%)	100	29	17	17
Min. air temp. (C)	10.56	7.15	9.19	8.62
Mean air temp. (C)	15.09	12.41	13.74	13.42
Max. air temp. (C)	21.89	18.76	18.76	20.98
Min. relative humidity (%)	39.1	48.7	51.2	35.8
Mean relative humidity (%)	77.3	80.7	83.6	67.0
Max. relative humidity (%)	97.0	97.25	95.2	91.9
Measured evaporation (mm/day)	3.7	4.1	1.0	2.0
Predicted open water evaporation (mm/day)	3.7	3.1	2.8	5.9
Measured evap./ open water evap.	1.0	1.32	0.36	0.34
Measured equiv. evaporation from net water surface (mm/day)	3.7	14.0	6.0	11.7
Measured equiv evap./ open water evap.	1.0	4.52	2.14	1.98

### 3. RESULTS AND DISCUSSION

The physical configuration of each test, its ambient conditions and key results are summarised in Table 1. Figure 3 shows the raw water level time series records obtained for each test. Figure 3 shows that in each test case, the evaporation rate remains approximately constant but with some weak modulations, due to changes in the ambient temperature and humidity.

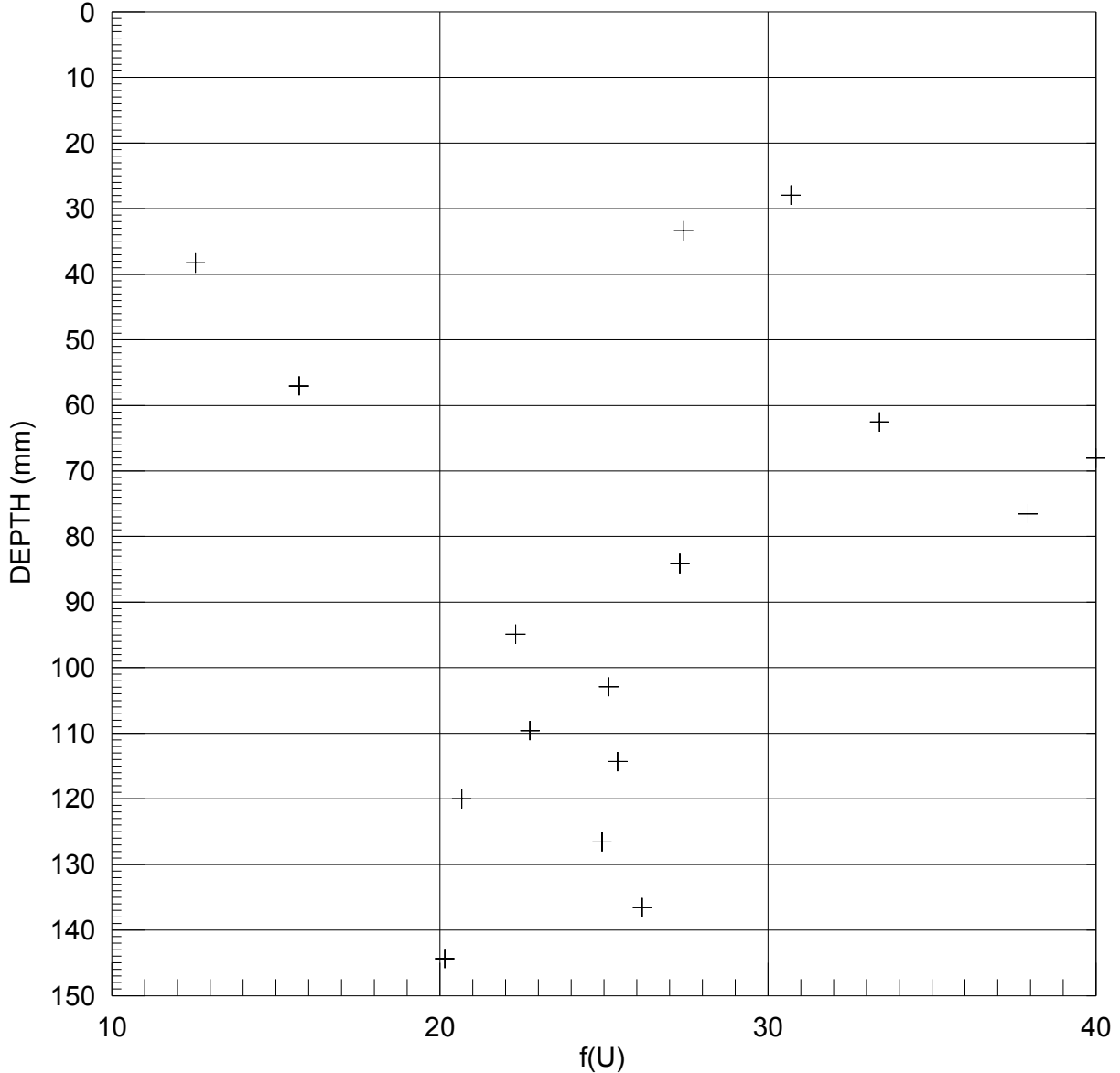


Figure 4. Measured variation of the value of  $f(U)$  as a function of depth.

#### 3.1. System Characterisation

To eliminate the effects of temperature and humidity variations between each test, conventional evaporation corrections have been applied to the data as follows. The design of the test rig precludes incoming solar radiation. By 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  $E$  ( $\text{mm}\cdot\text{day}^{-1}$ ) can be expressed in a form developed by Penman (1948):

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

where  $\gamma$  is the psychrometric coefficient in  $\text{mbar.K}^{-1}$ ,  $\Delta$  is the slope of the saturation water vapour pressure curve in  $\text{mbar.K}^{-1}$ ,  $e_{sat}$  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 ( $\text{mm.day}^{-1}.\text{kPa}^{-1}$ ) function of the wind velocity above the surface (Peirson *et al.*, 2011). Note that  $f(U)$  is influenced by the surface roughness.

The term  $f(U)$  should be remain independent of depth for a tank containing only water. By measuring evaporation from the tank containing only clean water,  $f(U)$  was computed for the constant wind velocity used during the experiments. The data obtained from almost 34 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. Although no systematic variation in  $f(U)$  with depth can be observed, the data at a depth less than 75mm is more scattered. Averaging the present data yields a mean value of 26.8 with a standard error 2.01 in reasonable agreement with the previously determined value of 22.3 with a standard error 1.27 previously determined by Peirson *et al.* (2011). For all subsequent processing, an average value of  $f(U) = 26.8$  has been retained.

Once the floating modular devices were in place, the recorded temperature and humidity data were used to compute the evaporation rates that would have occurred from open water using equation (1).

### 3.2. Evaporation in the presence of surface-sheltering devices

The average increases or reductions in evaporation that occurs in the presence of surface-sheltering devices are summarized in Table 1.

The influence of the enhanced adhesive processes over the surface of the tennis balls is significant and increases the evaporation by approximately 32%. Therefore, the surface properties of surface-sheltering devices can play an important role in determining whether a net benefit in evaporation reduction is obtained.

However, with the clean polyethylene balls in place, evaporation is reduced significantly by approximately 65%. This result highlights the potential reductions that can be achieved by sheltering the surface in this manner.

Once the polyethylene balls are contaminated with a surface slime, Figure 2 and the values in Table 1 suggest that the evaporation rate is enhanced by approximately 100%. However, once the temperature and humidity corrections are applied to the data, the characteristic reductions in evaporation rate associated with the clean and slime-contaminated devices are almost indistinguishable.

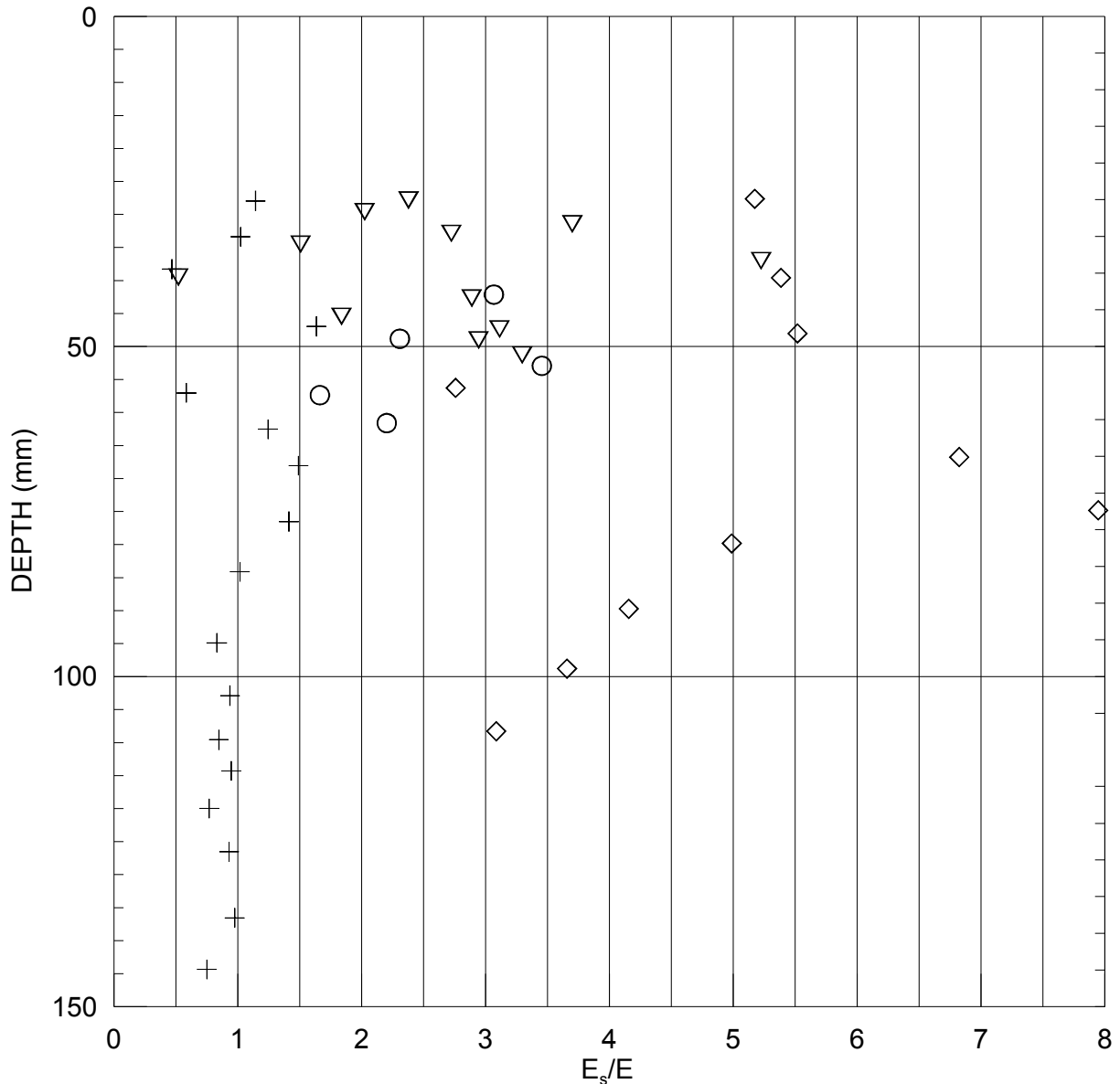
### 3.3. Impact of adhesive and capillary processes

The relationship between adhesion and evaporation can now be explored. The local evaporation rate  $E_s$  occurring from the exposed surface area of water can be found by multiplying the observed evaporation rate  $E_M$  by the ratio of the total surface area of the water tank  $A_T$  to the actual exposed water surface area  $A_s$ . To obtain an adhesion coefficient  $\alpha_E$  which captures the effects of capillarity between the individual sheltering units as well as the effects of the surface properties of the units, the local evaporation rate is expressed as a proportion of that which would occur from open water  $E$  (Equation 1):

$$\alpha_E = \frac{E_s}{E} = \frac{E_M A_T}{E A_s} \quad (1)$$

This adhesion coefficient is shown as a function of depth in Figure 5. Although there is considerable scatter in the results, the mean values can be determined as shown in the last row of Table 1.

At depths greater than 75mm, the computed adhesion coefficient for the open water experiment is systematically slightly less (0.89) than 1 suggesting that the quantity  $f(U)$  has been slightly overestimated. Adopting the suggested revised value of  $f(U)$  of 23.8 is in closer agreement with Peirson *et al.* (2011) but does not significantly change the overall conclusions of this study.



**Figure 5. Computed adhesion coefficient as a function of depth.**

Enhanced adhesion that arises from the surfaces similar to tennis balls increases by roughly a factor of 5 the evaporation that would occur from the exposed water surface alone.

Even from the polyethylene surfaces, these effects increase the local evaporation rates by a factor of approximately 2.

During these experiments, the influence on wind-generated evaporation has been examined in isolation from that which occurs due to solar radiation effects and care should be exercised when extrapolating these results to the field where low wind conditions may dominate.

However, these results do highlight the potential of adhesive processes to enhance evaporation in the presence of surface sheltering devices and the potential importance of surface texture in determining net evaporation rate.

#### 4. CONCLUSIONS AND DISCUSSION

A laboratory investigation of the reduction in wind-forced evaporation that occurs in the presence of

surface-sheltering devices has been completed. Good repeatability using this experimental approach has been obtained.

The testing of devices with porous surfaces has shown that the actual evaporation rate with the devices installed can be higher than that which occurs at the surfaces of open water. Consequently, surface texture is important in determining device performance. This result also highlights the potentially significant contribution that the perimeter of a water storage may make to the total evaporation budget.

Devices with clean surfaces are shown to reduce wind-forced evaporation rate by approximately 65%. Assessment of the potential role of surface biological growth in reducing this effectiveness indicated that slimes do not significantly compromise the performance of such devices.

This investigation has not been able to incorporate wave-related processes including contact line motion or possible spray generation which may also enhance evaporation rate.

Further studies will be required to quantify the performance of surface-sheltering devices under conditions when solar radiation is the dominant contributor to evaporation.

This study also excludes other considerations relevant to use of such devices including their cost and fate under high rainfall conditions.

## 5. ACKNOWLEDGMENTS

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