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Evaporation from bare soil: Lysimeter experiments in sand dams interpreted using conceptual and numerical models

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ABSTRACT

Unlike evaporation from open water, the magnitude of evaporation from bare soil decreases as the water table falls. Bare soil evaporation studies have included field and laboratory experiments, mathematical formulations and semi-empirical models. However, there is only limited field information, especially concerning evaporation from bare sand. The semi-empirical approach of the FAO[1] Irrigation and Drainage Paper 56, which contains guidelines for computing crop water requirements, can be adapted for bare soil evaporation with a three stage process. The suitability of the FAO 56 approach for bare sand evaporation is investigated by installing lysimeters in sand dams. Sand dams are shallow groundwater storage systems, which are designed on the assumption of reduced evaporation as the water table falls. The field results from the lysimeters are simulated adequately by a water balance model based on FAO 56 with an additional component to represent both the difference between the variable saturation with depth, which occurs in practice, and the assumption in standard water balance models of a sudden change from dry to fully-saturated conditions at the water table. This study demonstrates and quantifies the reduction in bare soil evaporation compared to open water or cropped areas and confirms the validity of the three stage FAO semi-empirical approach.

1. Introduction

Evaporation from bare soil is an important component of the soil-water balance especially in semi-arid and arid locations. There is comprehensive information about open water evaporation (Shaw et al., 2010; Harwell, 2012) and evapotranspiration for well-watered crops (Allen et al., 1998; Jensen and Allen, 2016) but less information about bare soil evaporation. Of particular significance is the substantial reduction in bare soil evaporation as the water table falls.

There are several alternative approaches for investigating and quantifying bare soil evaporation, they include field and laboratory experiments, formulating mathematical expressions to represent the soil-water-atmosphere conditions (with numerical solutions for these equations) and semi-empirical formulations using meteorological parameters. Field experiments date back to early in the twentieth century (Harris and Robinson, 1916); Hellwig (1973a) describes long term experiments using deep lysimeters in a sand river bed in South Africa to estimate actual evaporation with the water table maintained at specified depths. Further field experiments where the soil is predominantly bare are reported by Mutziger et al. (2005). Examples of laboratory experiments, which aim to represent meteorological and soil conditions include Zarei et al. (2010), Smits et al. (2012), Davarzani et al. (2014), Tran et al. (2016), Davarzani et al. (2014) also provide a detailed review of the many attempts to develop mathematical formulations to represent evaporation from bare soil; they also present a new approach for estimating the rate of soil evaporation and its dependence on atmospheric conditions and thermal and hydraulic properties of the soil. Further examples of numerical models to represent the process of evaporation from bare soil are reported in Bittelli et al. (2008), Smits et al. (2012), Tran et al. (2016). However, most estimates of crop evapotranspiration and bare soil evaporation are based on semi-empirical models such as that of Penman-Monteith (Ward and Robinson, 1990; Allen et al., 1998).

When adopting semi-empirical approaches to estimate evaporation in field conditions, there are two important aspects to be considered. The first is to estimate the potential bare soil evaporation and how it is modified by physical features in the surrounding area. Valuable insights and information, developed by an international panel of experts, are included in the FAO Irrigation and Drainage Paper No 56, "Crop evapotranspiration: guidelines for computing crop water requirements"

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[1] ETo – Evapotranspiation; FAO – Food and Agriculture Organisation; REW – Readily Evaporable Water; TEW – Total Evaporable Water.

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(Allen et al., 1998). It recommends using meteorological data as inputs to the Penman-Monteith methodology for estimating the potential evapotranspiration for a reference crop; this reference evapotranspiration can then be modified using factors to provide estimates of bare soil evaporation. The second aspect is to estimate how the actual evaporation changes as the water table in the soil falls? Mutziger et al. (2005) propose a three stage modification to the FAO 56 methodology to estimate the reduction in evaporation as the water table falls; their methodology is checked against field experiments in loam and clay soils but its validity for extensive sand deposits has not been confirmed. Consequently, due to the limited information about evaporation from bare soil in field situations, further field studies are required.

The reduction in bare soil evaporation at deeper water table depths (Hellwig, 1973a) is the basis of the extensive development of sand dams in eastern Africa (Hut et al., 2008; Maddrell and Neal, 2012). Water losses occur from open water reservoirs due to evaporation; these losses are substantial during hot dry seasons. One approach to limiting these losses is by forming sand reservoirs (which are conventionally described as sand dams) in river valleys. A conventional dam is constructed across a valley; sand and water collect upstream of the dam as the river floods during rainy seasons. When the water table in the sand falls by more than about 0.6 m the actual daily evaporation is less than the daily evaporation from a conventional water filled reservoir (Hut et al., 2008; Maddrell and Neal, 2012; Neal, 2012). However, there is little field evidence to quantify this difference.

In an investigation of the behaviour of sand dams in Kibwezi, Makueni County, Kenya, lysimeters were installed in two of the relatively small sand dams during the dry season of 2017. The sand in Dam 106 extends more than 300 m upstream of the dam; the bed slope is approximately 0.6% and the depth of sand is more than 2.5 m. For Dam 167, the sand extends nearly 500 m, the bed slope is 0.45%; close to the dam the depth of sand is 2.5 m but decreases to 1.2 m where the river bed ends abruptly with large boulders blocking the width of the channel. In each of the dams, one lysimeter was located not far from the dam and a second lysimeter further upstream where the valley is narrower. Three experiments were carried out in each lysimeter; the fall in the water table due to evaporation was monitored using piezometers. Since the lysimeters were located in areas where the public had access, the top of the lysimeters were at ground level and were camouflaged to discourage interference.

Interpretation of the results from the lysimeter experiments requires estimates of the potential evaporation and how it is reduced due to falling water tables in the sand. Since the sand dam lysimeters are located in narrow valleys, potential evaporation varies due to differing wind speeds and shading. Conceptual and computational models are developed for water balance calculations which predict changes in water levels in the lysimeter.

The first section of this paper identifies important insights about the processes involved in bare soil evaporation, and describes semi-empirical methods of estimating both potential and actual evaporation. Results from the lysimeter experiments are examined and the initial rapid fall in the piezometer readings noted. Conceptual and computational models are developed with special emphasis on a modification due to the assumption in the computational model of a sudden change from dry to fully-saturated conditions and also to make allowance for air trapped during the filling of the lysimeters.

2. Insights from previous studies of evaporation from bare soil

Quantifying actual evaporation from a bare soil surface involves an estimation of the potential evaporation followed by adjustments to allow for reduced evaporation as the water table falls.

2.1. Estimation of bare soil (sand) potential evaporation

Evapotranspiration is frequently estimated using the Penman-Monteith equation which provides daily estimates of evapotranspiration, ETo, for a reference surface of grass which is constantly growing, (Ward and Robinson, 1990; Allen et al., 1998). The reference surface closely resembles an extensive surface of green, well-watered grass of uniform height, actively growing and completely shading the ground. Evapotranspiration for other crops is estimated by multiplying the reference evapotranspiration by crop coefficients which frequently vary during the growing season and fall significantly at harvest. For example the crop coefficient for wheat changes from Kc = 0.4 at sowing, 1.15 during mid season and 0.25 at harvest. For sugar cane the values are 0.40, 1.25 and 0.75, whereas for pineapple the values are 0.50, 0.30 and 0.30. A non-varying crop coefficient is used to estimate bare soil potential evaporation from potential evapotranspiration; this coefficient Ke = 1.05 (Allen et al., 1998).

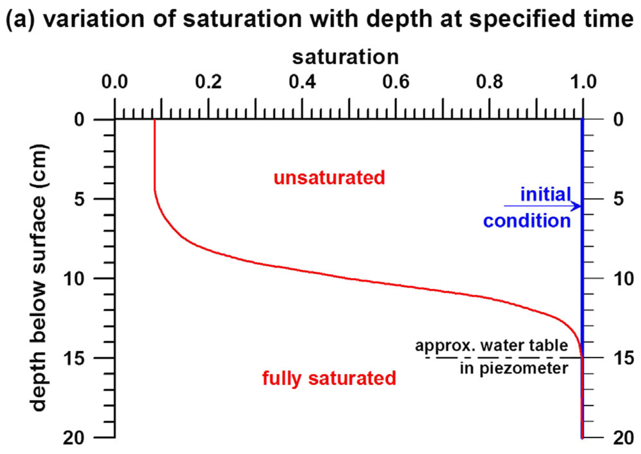
Since there are no weather stations in the vicinity of the sand dam sites, the Penman-Monteith method cannot be used. However the FAO Irrigation and Drainage Paper 56 (Allen et al., 1998) suggests that "When solar radiation data, relative humidity data and/or wind speed data are missing.. ETo can be estimated using the Hargreaves ETo equation". The Hargreaves equation (Hargreaves and Samani, 1985) requires the maximum and minimum daily temperatures; it also takes account of the latitude and the elevation of the sun. The adequacy of Hargreaves method is discussed in Hargreaves and Allen (2003); they conclude that the Hargreaves ETo method produces values for periods of five or more days that compare favourably with those of the FAO Penman-Monteith method.

Techniques such as the Penman-Monteith and Hargreaves equations are suitable for extensive cultivated areas where there are no physical features causing a disturbance. However in sand dam, which are located in valleys, features such as differences in wind speed and shading due to the valley sides or trees can modify the potential evaporation. Various factors which can influence potential evaporation have been explored using field experiments. A paper published 1916 with the title "Factors affecting the evaporation of moisture from the soil" (Harris and Robinson, 1916) describes a study by F. H. King which compares evaporation from a wet soil located 300, 150 or 20 ft (91, 46 or 6 m) from a hedgerow. At 46 m the evaporation is 93% of the evaporation with the hedgerow at 91 m, the corresponding evaporation at 6 m is 77%. Harris and Robinson's own studies show that wind speed has a substantial effect on evaporation. At about 9 m/s the evaporation reached a maximum; at 4.5 m/s the evaporation was 90% of the maximum with 75% of the maximum with a wind speed of 2.2 m/s. Davarzani et al. (2014) simulated different wind speeds in laboratory experiments and show that for a wind speed of 3.6 m/s, the evaporation is between 1.5 and 1.2 times the evaporation for a wind speed of 0.5 m/s. Hellwig (1973a) and Tran et al. (2016) also emphasise the significant effect of the wind speed on evaporation.

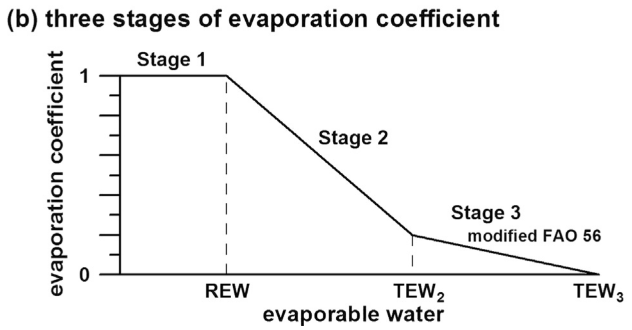
2.2. Dependence of actual evaporation from sand on depth to water table

An important feature claimed for sand dams is that the evaporation becomes negligible when the water table is more than 60 cm below the ground surface (Maddrell and Neal, 2012; Neal, 2012). This assertion is based on the detailed field experiments (Hellwig, 1973b) which provided data about the actual evaporation from bare soil when the depth of the water table below the soil surface is held at a constant value. Hellwig's results are summarized by Mansell and Hussey (2005) who relate evaporation from sand to open water evaporation. When the water table is at ground surface, 30 cm below the ground surface or 60 cm below the ground surface, evaporation for coarse sand is 0.90, 0.29 or 0.11 of the open water value. For medium sand the corresponding fractions are 0.92, 0.45 or 0.11.

An approach to the estimation of actual evaporation from a bare surface sands and the resultant drying of the sand is presented in Chapter 5 of Hillel (1980). "Soil-moisture evaporation occurs under unsteady conditions and results in a net loss of water from the soil, i.e. it



(a) variation of saturation with depth at specified time



(b) three stages of evaporation coefficient

Fig. 1. Features of evaporation (a) experimental saturation curve as evaporation occurs from sand surface (deduced from Smits et al., 2012, Davarzani et al., 2014), (b) FAO approach for reduction in evaporation as water table falls (derived from Mutziger et al., 2005).

results in drying. There are three recognisable stages."

(1) An initial *constant-rate* stage, while the soil is wet and able to supply water to the soil surface at a rate adequate for the evaporation demand, hence the evaporation rate depends on external meteorological conditions.
(2) An intermediate *falling-rate* stage when the evaporation rate falls progressively below the potential rate; the evaporation depends on the rate at which the drying soil profile can transmit moisture to the soil surface.
(3) A residual low *rate-stage* which is established eventually and which may continue for weeks or months.

Valuable insights into the soil moisture conditions during evaporation and the resultant drying of a soil are provided by laboratory experiments involving a wind tunnel, interfaced with a soil tank, instrumented with a network of sensors to measure soil-water variables (Smits et al., 2012; Davarzani et al., 2014). The experiments use a uniform silica sand (of largely uniform rounded grains); a typical result, Fig. 1(a), shows the distribution of saturation against depth. This distribution of saturation indicates that the conventional assumption of largely dry sand above a "water table" and fully saturated below is not strictly correct, especially in the early stages of evaporation. Fig. 1(a) also indicates the approximate water level when a piezometer is used to monitor conditions in the soil. Several experimental studies including Mutziger et al. (2005), Davarzani et al. (2014), Tran et al. (2016) indicate that there is often a continuing evaporation of roughly 10% of the potential rate for 20 or more days after the start of the experiment.

A practical approach to the estimation of evaporation from bare soil, and the resultant fall in the water table, is described by Mutziger et al. (2005). It is an adaptation of the FAO 56 methodology for estimating evaporation when there is limited availability of water. It uses the concept of Readily Evaporable Water, REW, and Total Evaporable Water, TEW, with Stage 1 and Stage 2 evaporation as described in Fig. 38 of Allen et al. (1998). Stage 3 evaporation, Fig. 1(b), is added to represent the slow and steady vapour transfer rate between moist deep soil and the dry air above, or with soil cracking that exposes deeper soil to the surface evaporation potential, (Allen et al., 2005).

Mutziger et al. (2005) review seven field experiments of evaporation from bare or near-bare soil (when the Leaf Area Index ≤ 0.15); the soils were black clay, clay loam, silt loam and sandy clay loam. For each of the field studies either precipitation or irrigation occurred during the study period; in most studies evaporation fell to about 10% of the potential value. The measured and the modified FAO-56 simulated evaporation and cumulative evaporation trends and values were similar.

2.3. Summary of insights

- Potential evapotranspiration can be estimated using the Penman-Monteith approach; in the absence of detailed meteorological information the Hargreaves method can be used.
- Potential evapotranspiration can be converted to potential evaporation for bare soil using a 'crop coefficient' which is taken as 1.05.
- Potential evaporation is modified significantly due to changes in wind speed and the presence of shade.
- There are three recognisable stages in actual evaporation from bare surface soils, an initial constant-rate stage, an intermediate falling-rate stage and a residual low-rate stage.
- The modified FAO 56 methodology (Mutziger et al., 2005) provides a practical approach for estimating the actual evaporation as a function of the water table depth. It depends on estimates of the readily evaporable water and total evaporable water for the soil.

3. Lysimeter experiments in sand dams

Table 1 describes the locations of the lysimeters; two lysimeters of 60 cm depth and 50 cm diameter were installed at each of the sand dams; one was located within 20 m of the dam wall and the other three quarters of the way along the investigation area. Three experiments were conducted in each lysimeter. The procedure adopted for each experiment was to fill the lysimeter in layers with sand and water with the sand agitated in an attempt to displace any trapped air. Emptying and re-filling each lysimeter for the next experiment took half a day. A piezometer was installed in each lysimeter and the fall in water level in the lysimeter due to evaporation recorded over a period of three weeks in the first experiments and two weeks for the subsequent experiments.

A preliminary examination of the field results concentrates on two lysimeters experiments in Sand Dams 106 and one in Sand Dam 167. The field readings, indicated by symbols in Fig. 2, are joined by spline smoothed lines.

For each of the lysimeters there was a vary rapid fall in the water table in the first day (0.23 and 0.26 m), a smaller fall during the second day (0.09 and 0.05 m) with a still smaller fall during the third day (0.06, 0.03 m); after about 8 days there is a roughly steady decline. There are three main reasons for the initial rapid fall:

1. the rate of evaporation from the sand surface reduces as the water

Table 1
Description of experimental plan, including experimental locations.

Location on sand dam	Dam 106	Dam 167
20 m from dam wall	3 repetitions	3 repetitions
¾ distance along investigation area	3 repetitions	3 repetitions
20 m from dam wall	3 repetitions	3 repetitions
¾ distance along investigation area	3 repetitions	3 repetitions

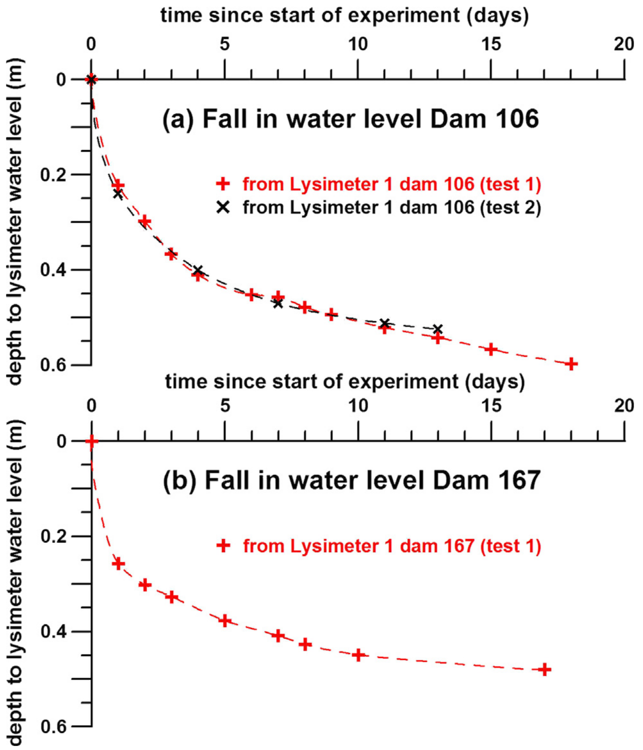


Fig. 2. Selected results illustrating the fall in water levels with time in lysimeters in Sand Dams 106 and 167.

table falls (see FAO three stage diagram, Fig. 1(b)),

2. when filling the lysimeters with sand and subsequently saturating the sand, not all of the trapped air was displaced,
3. there is not a sudden change between fully saturated and dry conditions; instead there is a gradual change in saturation as illustrated in Fig. 1(a).

The inclusion of these features in conceptual and computational models is described in the following section.

4. Conceptual and computational modelling of sand dam lysimeter response

Understanding and interpreting conditions in the sand dam lysimeter requires the development of conceptual and computational models, Figs. 3 and 4. Fig. 3 illustrates a conceptual understanding of the physical processes; Fig. 4 is a computational model which includes idealisations. When evaporation occurs from a lysimeter, the saturation decreases resulting in a lower actual evaporation as described by Hillel (1980), see Section 2.2. In the computational model the idealisation of a water table is introduced with dry sand above the water table and fully saturated sand below the water table.

Fig. 3 illustrates the physical conditions for a vertical section in a lysimeter:

i the potential bare sand evaporation of ET_{bs} is drawn above the section,
ii some air was trapped while the lysimeter was filled with sand and water,
iii the saturation on the vertical section, see Fig. 1(a), varies with depth as indicated in Fig. 3(a),
iv the lower part of the section is saturated,
v the upward movement of water, which is the actual evaporation at the soil surface, is shown in diagram (b); it becomes less than the potential evaporation rate.

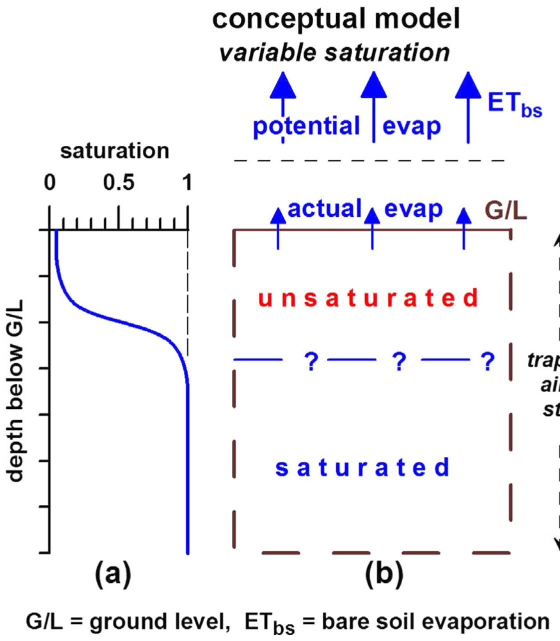


Fig. 3. Conceptual model of conditions in a sand lysimeter as the water table falls due to evaporation.

The idealised conditions incorporated in the computational model are indicated in Fig. 4:

i the potential bare sand evaporation ET_{bs} is drawn above the section, diagram (b)
ii The important idealisation is that the saturation suddenly changes from dry to fully-saturated at the water table as indicated in the diagram, Fig. 4(b); this idealisation is introduced in most techniques for estimating the actual evaporation.
iii there is a difference between the variable saturation that actually occurs, Fig. 3(a) and the idealisation in the computational model of a sudden change, Fig. 4(a). Furthermore, a piezometer in the lysimeter records a water level which is close to the elevation of full saturation as indicated in Fig. 1(a); this water level is described as the water table. The difference between the variable saturation of the conceptual model and the sudden change from dry to fully-saturated of the computational models is represented by introducing a storage reduction factor S_{fac}. This reduction factor increases from a low value when the water table is close to the soil surface to unity after a specified number of days as illustrated in Fig. 4(d). The reduced storage is significant during the early days of the lysimeter experiments,
iv the release of the air trapped at the start of the simulation is also represented using the storage reduction factor,
v the actual evaporation from the ground surface is less than the potential value; it is estimated using the three stage relationship from the FAO 56 approach as shown in Fig. 4(c). The evaporation factor $evap_{fac}$ depends on the current depth of the water table below the ground surface.

The water balance calculation for the sand in the lysimeter provides estimates of the *depth of water* that evaporates; this is termed the *effective depth*. It is important to recognise the difference between this *effective depth* of water and the corresponding *depth to water table* in the piezometer. The depth to the water table equals the *effective depth* of water that has evaporated divided by a storage coefficient, S_D. This storage coefficient is the volume of water, per unit volume, which the gradually drying soil profile can deliver to the soil surface. This is a different from the situation when water is drawn from the soil by the

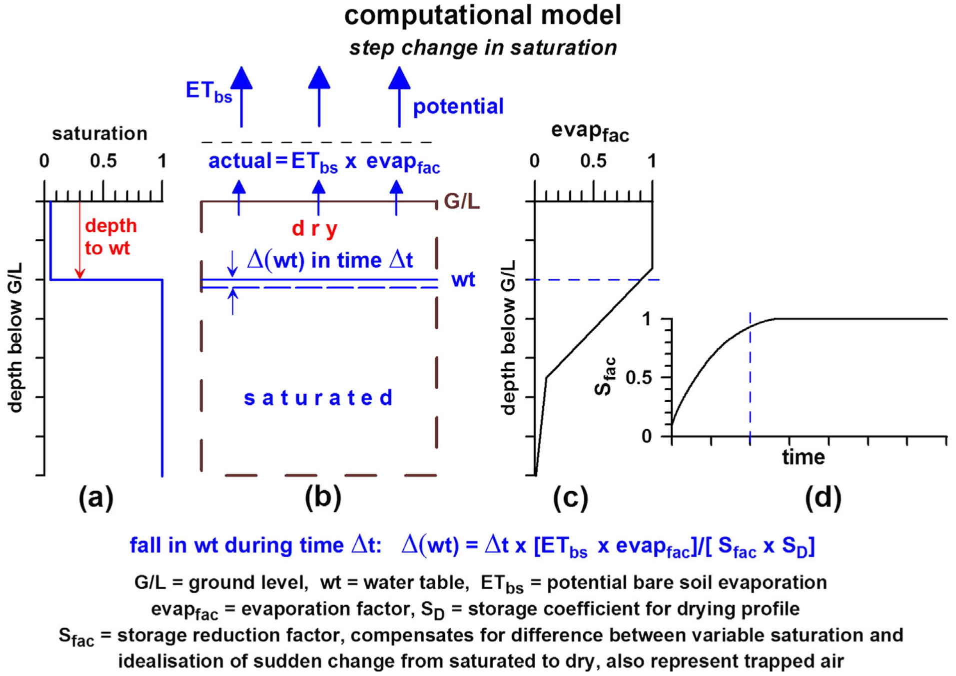


Fig. 4. Computational model for evaporation from a lysimeter containing sand: (a) assumption of sudden change in saturation at water table, (b) actual evaporation and fall in the water table, (c) change of evaporation factor with depth to water table, (d) change of storage reduction factor with time.

roots of crops. Furthermore, S_D is not the same as the specific yield (or drainable porosity) which is defined as the volume of water, per unit volume, which drains under gravity.

Consequently the fall in the water table during a time increment Δt can be calculated as follows

$$\text{incremental water table fall} = \Delta\, t \times [ET_{bs} \times evap_{fac}]/[S_{fac} \times S_D]$$

5. Comparison of lysimeter readings and computational model

Computational models, which reproduce the observed water table fall in the lysimeters, are described below.

5.1. Lysimeter 1 sand dam 167 in vicinity of dam

Due to the absence of operating meteorological stations in the vicinity of the study areas, the bare sand potential evaporation is estimated using the method of Hargreaves (Hargreaves and Samani, 1985, Hargreaves and Allen, 2003). A template for the application of Hargreaves method is available in FAO 56 (Allen et al., 1998). It requires an estimation of the radiation (values obtained from Table 2.6 of Annexe 2) and the maximum, minimum and mean temperature.

For a latitude of 2°S, using Table 2.6 Annexe 2 of FAO 56, for June 1st $R_a = 33.4/2.45 = 13.63$

also $T_{max} = 35\ °C$, $T_{min} = 17\ °C$ and $T_{mean} = 26\ °C$

therefore the potential evapotranspiration

$$ET_o = 0.0023(T_{mean} + 17.8)(T_{max} - T_{min})^{0.5}\, R_a = 0.0023 \times 43.8 \times 180.5 \times 13.63 = 5.8\ \text{mm/d}$$

Bare soil evaporation equals the evapotranspiration multiplied by the coefficient 1.05.

The computational model for Lysimeter 1 of Dam 167 is chosen to illustrate how parameters for the model are selected. To define the variation of the evaporation factor with the *effective depth* to the water table, Fig. 5(c), estimates of the total evaporable water, TEW_2, and the readily evaporable water, REW, are required. Using Table 19 of Crage values for sand, $TEW_2 = 0.09z_e$ mm; where z_e is the depth of the layer

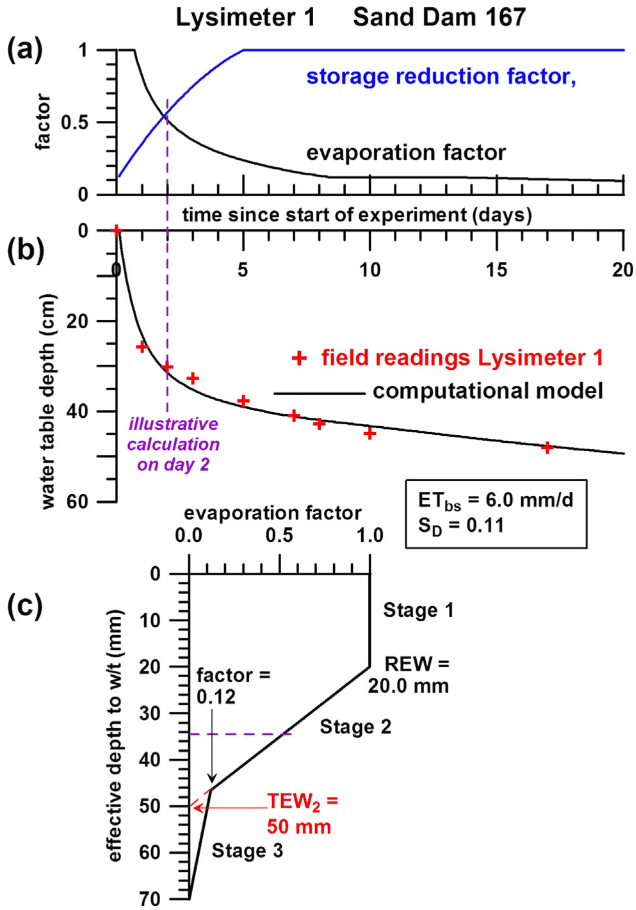


Fig. 5. Numerical model to represent experiment in Lysimeter 1 of Sand Dam 167: (a) storage reduction and evaporation factors, (b) depth to water table, (c) effective depth to water table and corresponding evaporation factors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

that is subject to drying due to evaporation. From lysimeter results, this depth is more than 55 cm hence $TEW_2 = 50$ mm. REW is set at 20 cm and the water content below which no evaporation occurs $TEW_3 = 70$ mm. Transition from the second stage to the third stage occurs when the evaporation factor is 0.12. In the absence of detailed information about the variation with time of the potential evaporation, a constant value of 6.0 mm/d is used.

An equation for the variation of the storage reduction factor S_{fac} with time must be developed. A quadratic relationship for the first five days is chosen. After five days the approximation of a sudden change in saturation from dry to fully-saturated is appropriate; in addition most of the trapped air has dissipated. Using an iterative procedure to achieve an acceptable match between field readings and model predictions, the following relationship was devised where *t* is the time in days since the start of the experiment:

$$S_{fac} = 1 - 0.09(5-t) - 0.018(5-t)^2 \text{ for } t \leqslant 5.0$$

This relationship is indicated in Fig. 5(a) by the blue line.

To illustrate the calculation for a typical time step, numerical values for the lysimeter of Sand Dam 167 between days 2.0 and 2.1, $\Delta t = 0.1$ day, are presented in Fig. 6. Since the depth to the water table on day 2 is 31.39 cm, the evaporation factor is 0.52, hence the actual evaporation is 3.1 mm/d. The storage coefficient is selected as $S_D = 0.11$ and at 2.0 days $S_{fac} = 0.57$. The time to which this calculation refers is indicated by the purple broken lines in Fig. 5(a).

With these parameters and factors, satisfactory agreement is achieved between the piezometer readings in the lysimeter and model predictions, Fig. 5(b). The validity of the computational model with three stages in the evaporation processes is supported by this comparison; the inclusion of the storage reduction factor allows for the reproduction of the initial rapid fall in the lysimeter water table. However, there are insufficient data readings from the lysimeter to allow the third stage of evaporation for deeper water tables to be explored in detail. Nevertheless a continuing small evaporation at deeper water tables is confirmed by the results of Fig. 5(b).

A sensitivity analysis was conducted and indicates that the storage reduction factor must continue for about 5 days; when the factor extends for only 3 days the rapid water table fall during the first few days is not reproduced adequately. There is uncertainty about the magnitude of the potential evaporation; however a lower potential evaporation of 5.0 mm/d can be compensated by a reduction in the storage coefficient S_D to 0.103. A further parameter which is difficult to quantify is the total evaporable water, TEW_2. When TEW_2 is reduced from 50 mm to 40 mm, and the storage coefficient S_D is set to 0.095 an adequate agreement with the field results can be obtained, although the match with the field readings is not as close as that in Fig. 5(b). These examples illustrate the interaction between the storage reduction factor, the potential evaporation ETbs and the variation of the evaporation factor with depth. The limited precision of the field experiments mean that precise values of the important parameters cannot be obtained. However, the important conclusion from this sensitivity analysis is that the satisfactory simulations with each of these alternative sets of parameter values confirm both the validity of the three stage approach of estimating the actual evaporation, Fig. 1(b), and the inclusion of a storage reduction factor.

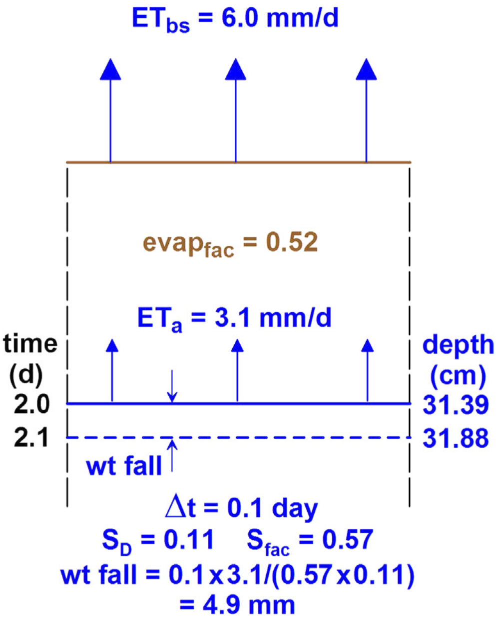


Fig. 6. Details of the water balance calculation between day 2.0 and 2.1.

Analyses were also carried out for Lysimeter 1 of Sand Dam 106; parameter values were only slightly different from Sand Dam 167 with $TEW_2 = 60$ mm rather than 50 mm and $S_D = 0.106$. The evaporation factor at the start of Stage 3 equals 0.16 compared with 0.12 in Fig. 5(c).

5.2. Lysimeter 2 sand dam 106 upstream of dam

Lysimeter 2 of Sand Dam 106 is located about 200 m upstream of the dam in the middle of the channel which is less than 5 m wide with vegetation on the banks. This situation is different from Lysimeter 1 where the location is more exposed with little vegetation or shade.

Field results for the first experiment in Lysimeter 2 are plotted in Fig. 7; the rate of fall in the water table in the piezometer is roughly half of that for Lysimeter 1. In the computational model, parameter values are modified from those for Lysimeter 1 to reflect the lower potential evaporation.

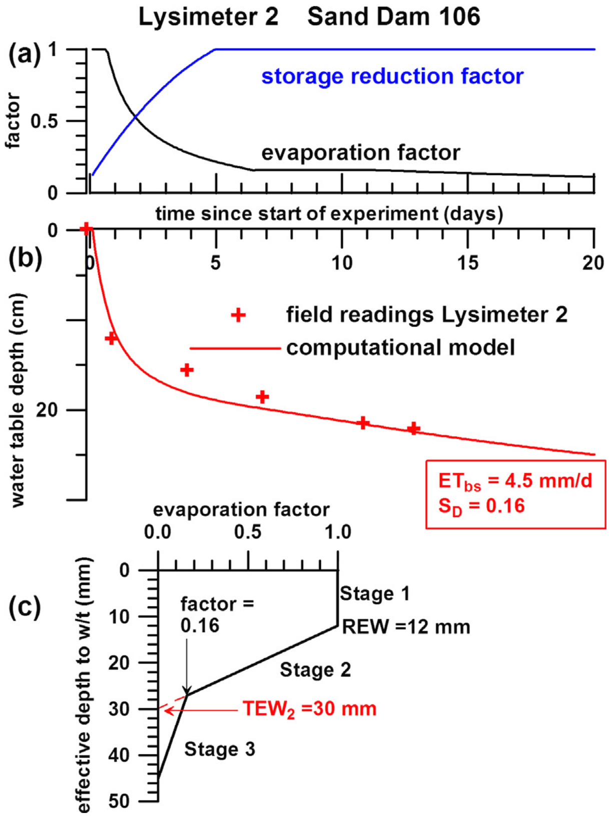


Fig. 7. Numerical model to represent experiment in Lysimeter 2, Sand Dam 106: (a) storage reduction and evaporation factors, (b) depth to water table, (c) effective depth to water table and corresponding evaporation factors.

- the three stage approach, to represent the reduction in evaporation as the water table falls, is consistent with the field results
- the potential evaporation takes lower values (4.5 mm/d compared to 6.0 mm/d for Lysimeter 1); this is appropriate since the wind velocities at Lysimeter 2 are lower and there is more shading,
- due to the presence of fewer fine particles, the total available water TEW_2 takes a lower value of 30 mm; this is consistent with Table 19 of Allen et al. (1998).

6. Conclusions

Evaporation from bare soils, and especially from sand, has been explored by conducting experiments in lysimeters. The construction and operation of the lysimeters was successful despite limited resources; the results confirm a significant reduction in actual evaporation as the water table falls. Furthermore, differences between results for lysimeters near dams and further upstream occur primarily due to the changed potential evaporation resulting from alternative wind conditions and increased shade.

Davarzani et al. (2014) explain that “Even though decades of research have improved our understanding of bare soil evaporation, many knowledge gaps still exist in the current science on how the soil water in the shallow subsurface close to the land surface interacts with the air in the atmosphere.” They quote more than thirty publications which attempt to develop computational models to simulate bare soil evaporation, but there are limitations for each of these approaches. Consequently in the current study, conceptual and computational models have been prepared based on a water balance approach using the FAO 56 semi-empirical model with modifications described by Mutziger et al. (2005). The computational model incorporates a three-stage evaporation process. Due to the difference between the variable saturation with depth which occurs in a lysimeter and the assumption in a water balance model of a sudden change from dry to fully-saturated conditions at the water table, a storage reduction factor is introduced. This storage reduction factor is also used to allow for air trapped in the lysimeter during the filling with sand and water.

Satisfactory agreement between the field and computational model results supports the FAO 56 three-stage approximation. Due to uncertainties about certain of the parameter values, sensitivity analyses were carried out; they indicate that with slightly modified parameter values, adequate simulations can be achieved. The experiments did not continue for long enough, nor were the lysimeters deep enough, to quantify accurately the reduced evaporation for deeper water tables; nevertheless limited evaporation does continue as the water table falls further.

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