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An examination of the hydrological system of a sand dam during the dry season leading to water balances

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ABSTRACT

To address water scarcity in semi-arid regions, rainfall and runoff need to be captured and stored locally before they are lost to the sea. This can be done using a sand dam which consists of a reinforced wall constructed during the dry season across a seasonal riverbed. However it is unclear whether their main utility is to store water in the sand that is also trapped behind them, or to facilitate aquifer recharge. This paper aims to answer this question by the calculation of a water balance in three sand dams in Kenya to quantify the amount of water transferred between the sand dam and the surrounding aquifer system. The components of the water balance were derived from extensive field monitoring. Water level monitoring in piezometers installed along the length of the sand deposits enabled calculation of the hydraulic gradient and hence the lateral flow between the different reaches of the sand dam. In one sand dam water was gained consistently through the dry season, in one it was lost, and in the third it was lost almost all the time except for the early dry season in the upper part of the trapped sand. In conclusion sand dams should not be treated as isolated water storage structures.

1. Introduction

In semi-arid regions reliable sources of water are essential to the local population wellbeing and socioeconomic growth (Lasage et al., 2008). One approach to achieving this reliable water supply is to increase local storage capacity utilising local experience in natural methods of water capture, filtration, storage and release (United Nations, 2007). Sand dams (also called sand-storage dams) have been successfully implemented in several semi-arid countries and are an example of such a system (Hut et al., 2008). A sand dam consists of a reinforced wall constructed on the bedrock during the dry season across a seasonal riverbed. During the rainy season, the sand carried by the river is deposited behind the wall; this accumulates until it is level with the top of the dam. The pore space in the sand is filled with water from the seasonal river which can then be abstracted by the local community during the dry season (Lasage et al., 2008). Evaporation of water from the sand deposits reduces significantly as the water table falls further below the ground surface (Hellwig, 1973a,b; Quinn et al., 2018a) a study of a sand dune aquifer, Mughal et al. (2016), also shows a reduction in evaporation as the water table falls. In order to retain water in the sand deposits the riverbed must be sufficiently impermeable.

Sand dams vary considerably in the area they cover; they can be 200 m wide (Neal, 2012) but most sand dams are no more than 20 m wide (Borst and de Haas, 2006; Nissen-Petersen, 2006). Research on Kenyan sand dams shows that only 1–3% of the river discharge is retained behind any individual sand dam, the remainder continues its natural course towards the ocean (Aerts et al., 2007). For the larger sand dams, infiltration galleries located on the river bed are preferred for abstracting water; for the smaller sand dams, hand dug wells and scoop holes are used.

There are several sources of guidance on the siting and construction of sand dams (Nissen-Petersen, 2006; RAIN, 2002; Maddrell and Neal, 2012). Fieldwork associated with understanding the hydraulics of sand dams is limited; the most comprehensive investigation is by Borst and de Haas (2006) who performed a rudimentary water balance. Other issues which are discussed in the literature include the capacity of sand dams for maintaining vegetation during drought (Ryan and Elser, 2016), their impact on the overall river catchment (Aerts et al., 2007; Lasage et al., 2008; Ertsen and Hut, 2009) and their water quality (Quinn et al., 2018b).

Borst and Haas (2006) present a helpful schematic diagram illustrating the flow components associated with a sand dam. Fig. 1 is a form of their diagram modified to represent conditions during a dry season. Water is lost from the sand deposits by evaporation, also water is

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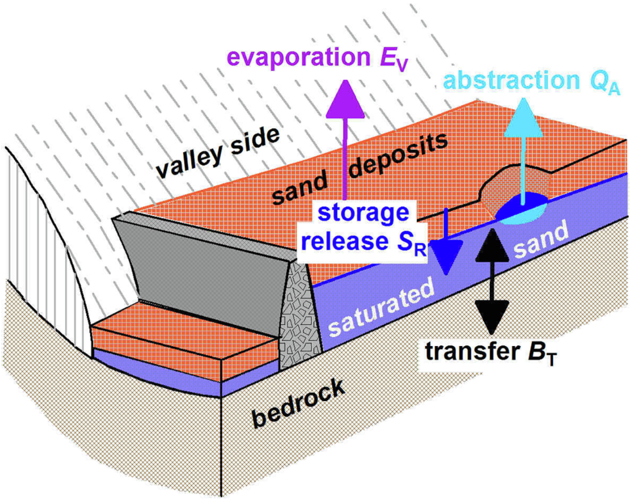


Fig. 1. Schematic diagram of a sand dam showing important flow components during the dry season.

abstracted from scoop holes or wide diameter wells. In addition water is released from storage as the water table falls. A fourth component of the water balance is defined in this paper as "transfer". Transfer refers to water which moves between the sand deposits and the surrounding aquifer system which includes the bedrock and the banks of the valley. This transfer can be in either direction.

The occurrence of these transfer flows is recognised in the literature. Munyao et al. (2004) explain that "The sand dam is simply a barrier in a drainage channel which holds sand and water on the upstream reservoir. It facilitates the percolation of water into the surrounding soil recharging the ground storage." Maddrell and Neal (2012), in their practical guide to sand dams, recognise that "Throughout the year, some of the water held in the sand dam will slowly permeate through the bedrock below and around the sides of dam." Hut et al. (2008) explain that "it is not clear to what extent dams can retain water, on what time-scales this retention will be effective, and how infiltration into the potentially large sub-surface reservoir happens." In none of the previous studies has this transfer been quantified although Borst and Haas (2006) suggest that 100 mm per year is a reasonable estimate. Lasage et al. (2015) and De Trincheria et al. (2018) assume that 5% of the total water yield is lost by seepage.

Water balances (or water budgets) are an important component of most hydrological investigations. Water balances can include large catchments or small areas; they can involve long time periods or only days or hours. In some circumstances, many of the components of the water balance can be measured or estimated accurately. In other situations a water balance is used to estimate a component which cannot quantified directly. For example, recharge can be estimated using a soil-water balance in which the recharge equals the residual (or out of balance) of the other components which include rainfall, runoff, evapotranspiration and water taken into soil storage. The major limitation of this residual approach is that the accuracy of the estimated recharge depends on the accuracy of the other components (Scanlon et al., 2002). The importance of carrying out a water balance before developing a computational model is stressed by Brassington and Younger (2010).

A number of attempts have been made to develop computational models for sand dams including Hoogmoed (2007), Hut et al (2008) and Quilis et al. (2009). While all of the authors acknowledge that water may infiltrate into the river banks, their models assume that the deposited sand is isolated from the surrounding aquifer system with the riverbed effectively impermeable.

The sand dams discussed in this paper are located in narrow valleys typically 10–15 m wide; hand pumps are not located on the sand deposits but are situated in the friable banks on the valley sides. The aim of this paper is to examine the water balances for three relatively small sand dams in Kibwezi, Makueni County, Kenya and, in particular, to quantify the transfer of water between the sections of the deposited sand and the surrounding aquifer system during the dry season. This is achieved by quantifying the components of the water balance based on individual reaches of the sand dam between regularly monitored piezometers and supported by lysimeter experiments to estimate the evaporation. By considering three sand dams it is possible to see whether there are different responses in individual sand dams. The sand dams are assessed on their ability to store water, their interaction with the surrounding aquifer system, water released from storage and evaporation losses. Through doing this, it is possible to determine the behaviour of these systems and their success at providing water storage throughout the dry season.

2. Methodology

2.1. Study area

The study took place in Kibwezi, Makueni County, Kenya. The average annual rainfall in this area is 600 mm and is characterized by small total amounts, and distinct seasonal distribution (Nyangito et al., 2008). The area experiences erratic rainfall distributed in two rainy seasons, known as the long and short rainy seasons. Long rains occur from March to May and the short rains from November to December, with the short rains being more reliable than the long rains (Gichuki, 2000). Three small scale sand dams constructed by African Sand Dam Foundation were selected for examination. The conditions for selection were that they contained sand and water at the end of the rainy season, and were within 30 km of the researchers' base at the town of Mtito Andei, allowing daily visits to the sand dams for monitoring.

2.2. Description of dams, valleys and sand deposits

Details of the sand dams are given in Table 1. The dams were all constructed in one stage over the course of a week with the sand deposited during the following year. Information in Table 1 is derived from a topographical survey completed at each sand dam using a dumpy level. The depth of the sand was determined by a probing method resulting in between 18 and 23 cross sections for each sand dam.

Fig. 2 includes plan views of the three sand dam sites. The positions of the installed piezometers (P) and local water abstraction points (hand pumps, scoop holes, open wells) are also shown. The length of the monitoring area varied between sand dam sites, this was determined by how the conditions of the deposited sediment changed upstream; when the sand became too coarse or stony it became impossible to install piezometers and hence the monitored section had to end.

At Dam 167 a flat rock face, about 3 m high, forms one bank. The other bank is as steep but shorter and consists of sandy clay overlying friable bedrock into which the hand pump was constructed. A stream runs from the rock located under the base of the dam wall which contains fish and is consistently pumped for irrigation purposes. Further upstream, the flat rock receded and both banks became similar in consistency with dense vegetation on both sides. A scoophole is positioned between P9 and P7 close to the river bank. The deposited sand becomes coarser away from the dam wall and ends abruptly with large boulders and rocks across the river bed.

Dam 211 is situated on the tributary of a larger river with a low flow throughout the dry season. On one side of the sand dam wall is a steep rocky bank at the top of which is farmland and housing, on the other side is farmland separated from the deposited sand by a short shallow clay bank on which the hand pump is located. Further upstream the steep rocky bank recedes, resulting in shallow sandy clay banks on both

Table 1
Description of Sand Dams and study areas.

Dam Number	106	167	211
Name	Ngulai	Athiani Farmers	Kipico Self Help Group
Year of construction	2013	2014	2015
Location (lat/long)	−2.550367 38.042371	−2.6033 38.10209	−2.56899 38.09542
Length monitored (m) (from final piezometer to dam wall)	250	480	380
Plan area (m^2)	4370	5230	3830
Volume (m^3)	6300	9235	8505
Bedslope (m/m) (Average slope from riverbed at final piezometer to riverbed at dam wall)	0.006	0.0045	0.007
Upstream conditions	Coarse sand and gravel; 300 m upstream of the last piezometer is another sand dam	Large rocks and boulders	Coarse sand to gravel; 500 m upstream is another sand dam
Downstream conditions from sand dam wall	Pools of water	Flowing water from dam base	Dry sand approximately 1 m deep

sides on which an open agricultural well is located. No pooled water or leakage was observed downstream of the dam wall. A scoop-hole is located between P2 and P7 close to the bedrock bank. Further upstream of the study site, the river channel becomes narrower; the deposited sand became coarser with small rocks and pebbles on the surface. Approximately 300 m upstream of the last piezometer there is another smaller sand dam without a hand pump.

2.3. Data and information collected

The water levels in the deposited sand were monitored using piezometers with an open section of 0.9 m. Between 7 and 9 piezometers were installed upstream of each dam wall following the channel of the river. Their installation sometimes proved difficult due to thick layers of clay throughout the deposits interspersing the layers of sand close to the dam wall and large boulders and rocks further upstream. Some of these

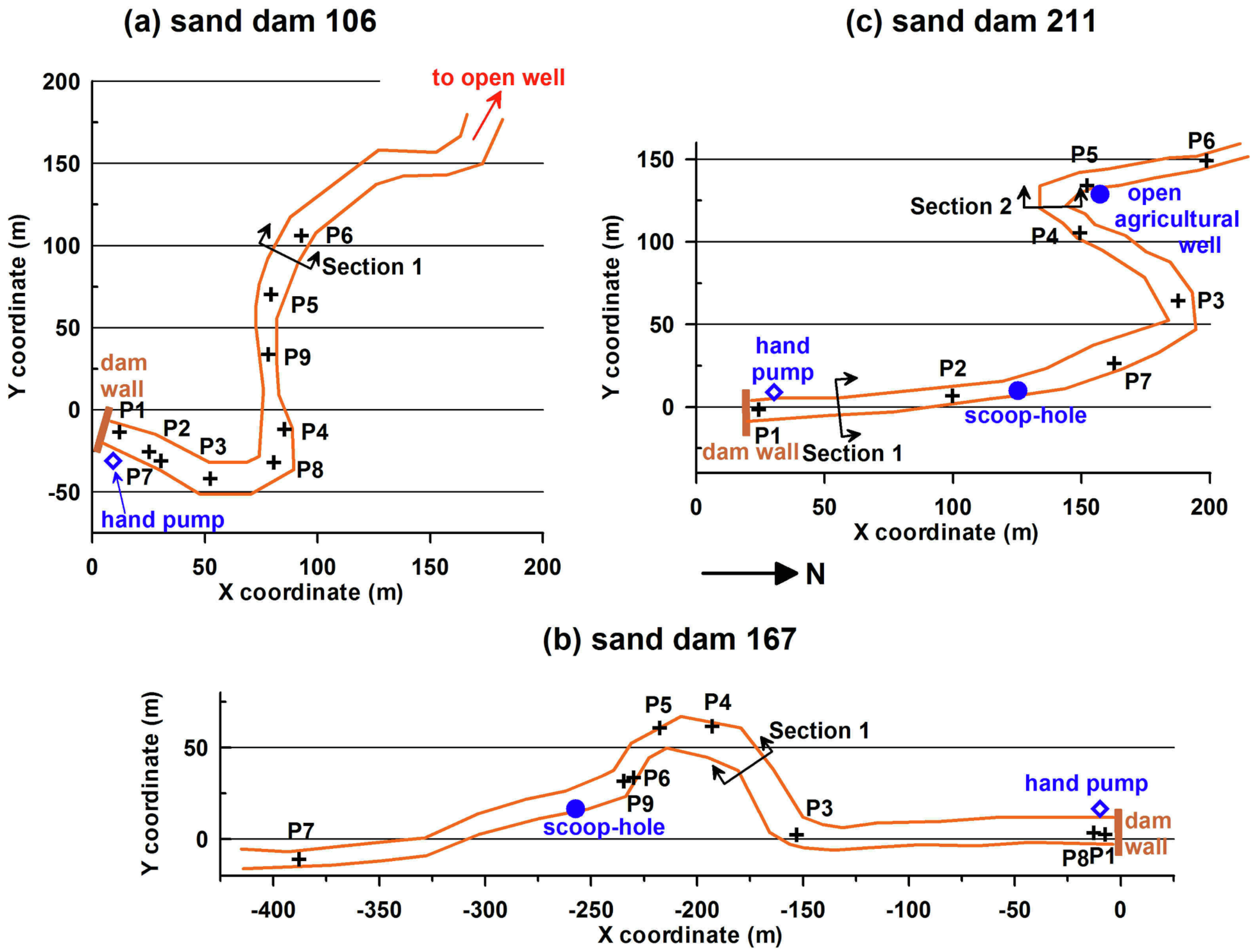


Fig. 2. Plan views of the sand dam sites (a) sand dam 106, (b) sand dam 167 and (c) sand dam 211. Dam 106 is surrounded by farmland with steep high banks composed of sandy clay leading to a sparsely vegetated plateau on one side and a steeply sloping rocky outcrop on the other. The hand pump is located on a flat part of this outcrop. Further upstream from P4 to P6 the banks become lower and shallower with gently sloping terraced farmland. Pooled water is located directly downstream of the dam wall; its level dropped throughout the dry season. Upstream of the study area the river channel branches off to several narrower tributaries; open wells are located along these branches which are used by the local population for drinking water and agriculture. There are no permanent scoop-holes.

piezometers became dry early in the season; sometimes they were replaced by additional deeper piezometers installed close by. Monitoring started 10 days after the last rain event with water levels recorded between 22/05/2017 and 26/07/2017 at a minimum of biweekly.

Two lysimeters of 60 cm depth and 50 cm diameter were installed at each sand dam. One was located near to the dam wall (< 20 m away) and the other three quarters of way along the study area. These were filled with saturated sand on three occasions. A piezometer was installed in each lysimeter and the fall in water table due evaporation recorded over a period of three weeks in the first instance and two weeks on the second two instances.

Sediment samples were taken at three cross sections in the deposits upstream of each sand dam, one section close to the dam wall, one at the mid-section and one at the end of the monitored section. Each cross section consisted of three auger points to abstract sediment. The sediment was categorized as sand or clay. Clay was differentiated from sand by examining the consistency of each of the samples, clay was found to be a stiff and sticky substance whereas sand was loose and granular. The sand samples were dried, sieved and the fractions classified into gravel, coarse sand, medium sand, fine sand and silt according to Wentworth (1922).

The salinity of the water in the sand deposits (monitored at piezometers and scoop-holes) and surrounding water sources (water downstream and open and closed shallow wells) was tested. Water was sampled from piezometers using a sterilized bailer and tubing. In scoop holes, water was first scooped with a sterile cup until the water appeared clear. For covered wells, water was pumped for thirty seconds before taking water samples. For open water sources a sterile cup was used to skim the sample from the water's surface. Finally, for open wells the local method of water abstraction was used (plastic bucket attached to rope) to collect samples. The collected water was transferred to 125 ml sterilised plastic bottles. Conductivity with measured with hand held probes. Two samples were tested at each abstraction location.

Pumping tests were used to obtain estimates of aquifer parameters for the deposited sand. Pumping wells were constructed using a rigid plastic hollow tube of diameter 0.6 m and depth 0.72 m; they were located in the vicinity of existing piezometers. Water enters through the base of the well as indicated in the conceptual model of Fig. 3(a). Pumping continued for 2 h; water levels in the well and the observation piezometer were also monitored during recovery. Tests were conducted at two locations in both sand dams 106 and 167. Observations were also made in a large diameter well in dam 211 that was being pumped for agriculture. Pumping at a rate of 288 m^3/d continued for 9.5 min and recovery was monitored for 270 min (4.5 h).

2.4. Calculating the water balance

Water balances have been calculated for reaches of the sand deposits between adjacent piezometers. Each balance includes the following inputs and outputs:

$$S_R + (F_I - -F_O) = E_V + Q_A + B_T \tag{1}$$

where S_R is the storage release as the water table falls, F_I is the flow into the reach from the upstream reach, F_O is the flow from the reach into the downstream reach, E_V is the evaporation, Q_A is the abstraction usually from scoop-holes and B_T is the transfer from sand deposits to the surrounding aquifer system. Units are m^3/d.

2.5. Sensitivity analysis

An issue of major significance in this study is the estimation of the transfer between the sand deposits and the surrounding aquifer system. The transfer is calculated as the residual of three quantities, the change in lateral flow, the evaporation and the water released from storage. When a quantity is estimated as a residual in a water balance (or water budget) calculation, the accuracy depends of the reliability of the other components (Scanlon et al., 2002). Uncertainties about parameter values are inevitable in groundwater studies (Anderson and Woessner, 1992; Rushton, 2003). For a sand dam analysis, uncertainties lie in the selection of the hydraulic conductivity, evaporation and specific yield. Consequently there are likely to be minor inconsistencies in the numerical values quoted for the transfer.

3. Results

The field study was completed between 11th May 2017 and 28th July 2017

3.1. Water level readings in piezometers

Fig. 4 shows the water levels at the piezometers for all three sand dams at four selected times during the monitoring period. All measured values are indicated by a symbol and these are joined by a line indicating measurements taken on the same day. Where the symbol is absent no measurement was possible. The base of the riverbed indicated by the black broken line is the average of the three lowest values at each probing location. This reduces the irregularities detected during the probing due to numerous boulders and pits in the riverbed. This results in several piezometers such as P9 (Dam 167) and P7 (Dam 106) appearing to extend beyond the base however they are simply located at a position where the base is lower than the average.

3.2. Initial water levels

At Dam 106 the initial water level was between 0.48 m and 1.25 m below the soil surface 10 days into the dry season. As is shown in Fig. 4(a) the water table is located closer to the surface upstream and decreases towards the dam wall. This indicates greater water loss in the area adjacent to the dam wall; this is consistent with the observation of water pooled downstream of the dam.

For Dam 167, Fig. 4(b) the initial water level was between 0.19 m and 0.92 m below the soil surface 12 days into the dry season. As shown in Fig. 4 the depth to water varies along the length of the deposited sand indicating potential areas of transfer flow into the sand between P9 and P3. The deepest depth is towards the dam wall which suggests leakage in this area. This was confirmed visually as water was seen to flow constantly from the base of the dam wall throughout the monitoring period.

At Dam 211 the initial water level was between 0.65 m and 1.42 m below the soil surface 14 days into the dry season. As shown in Fig. 4(c) the water table is located closer to the surface near to the dam wall but decreases further upstream from the dam wall. This is consistent with the location of a large diameter well (3 m from P5) which was pumped two or three times a week for irrigation, causing a decrease in the water level in the adjacent area.

3.3. Rate of water table decline

The rates at which water tables decline are shown on Fig. 4 with quoted values at either end of the monitored areas and for early and later in the dry season. The most rapid declines occurred in Dam 211. For Dam 106 the declines were also significant apart from reading 'a' which refers to the reaches between P6 and P5 early in the study period; subsequently it will be shown that this reduced decline is due to a transfer of water into the sand deposits early in the dry season. Although there was a significant decline in Dam 167 during the early dry season, probably due to the effect of evaporation, between 8th and 26th July the declines were just 0.6 and 0.4 mm/d.

3.4. Water table gradients

In all the sand dams, water moves downstream towards the dam

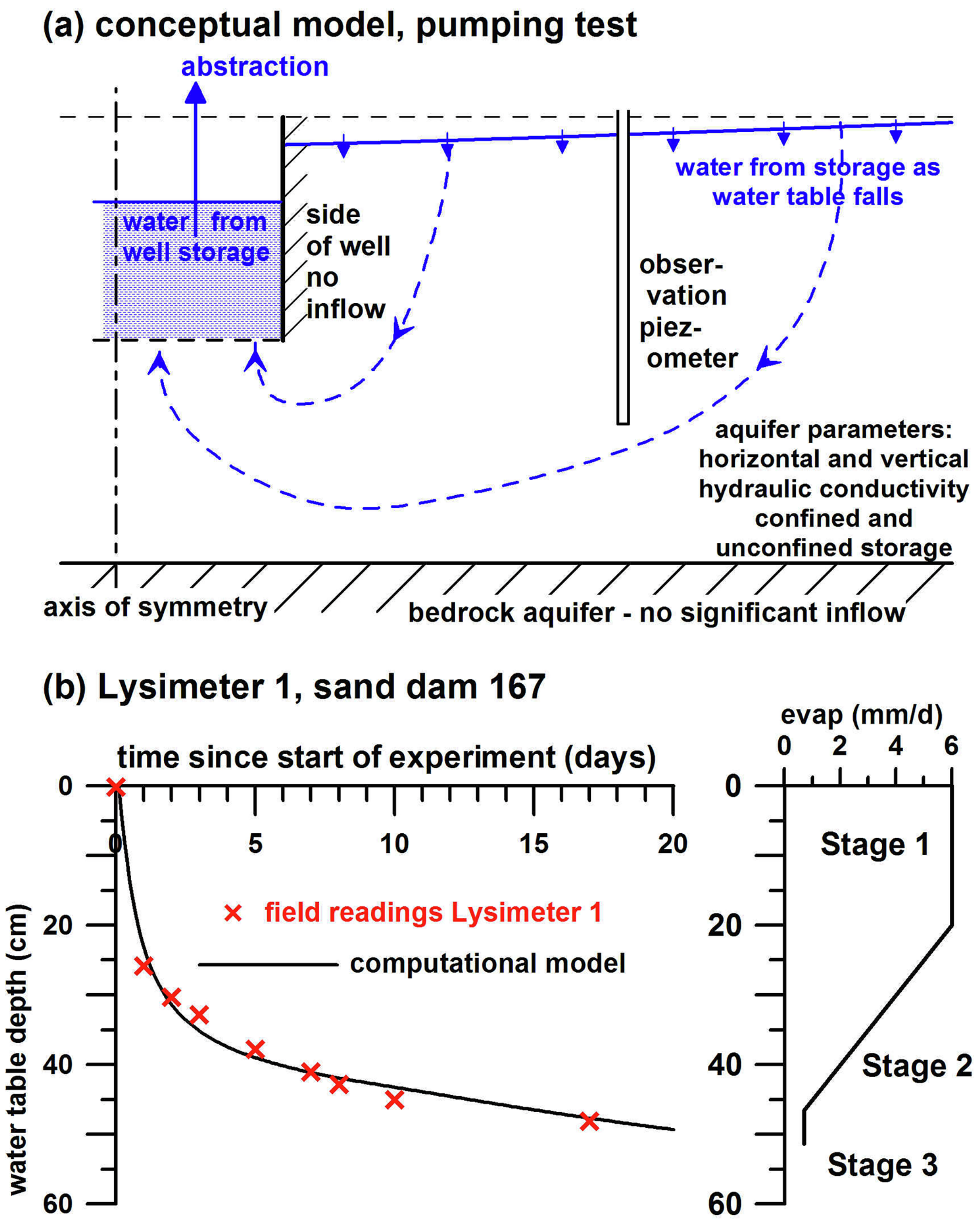


Fig. 3. Estimation of aquifer parameters and rate of evaporation from sand: (a) conceptual model for pumping from a partially penetrating well open at its base, (b) representation using a semi-empirical model of a lysimeter experiment.

wall as indicated by the hydraulic gradient. The gradients are almost constant with time with little variation (maximum 25%) between time periods. For Dams 106 and 211 the hydraulic gradient steepens towards the dam wall which indicates significant leakage and as mentioned above surface water was observed downstream. This is investigated further in the section 3.10. Remedial works were completed on Dam 211 during 2016 to minimize leakage and no water was observed directly downstream during the course of monitoring; this is confirmed by a shallower hydraulic gradient. There is a slight reversal of the hydraulic gradient between P5 and P4 at Dam 211 which is attributed to the presence of the large diameter well; which also causes the steep hydraulic gradient between P6 and P5.

The shape of the hydraulic gradient at Dam 167 is significantly different from those of Dam 106 and 211; it is less steep. This suggests transfer flow from the surrounding aquifer system to the deposited sand.

3.5. Sediment analysis

The sediment sampling revealed that there is often sticky lumps of clay in the deposited sand. Fig. 5 shows the sediment profiles for each sand dam. This suggests that the hydraulic conductivity of the deposits might vary significantly for each sand dam. In addition the mean percentage of silt (the finest fraction of the sieved sand) in dams 106, 167 and 211 was calculated as 1.8%, 1.2% and 1.4% respectively.

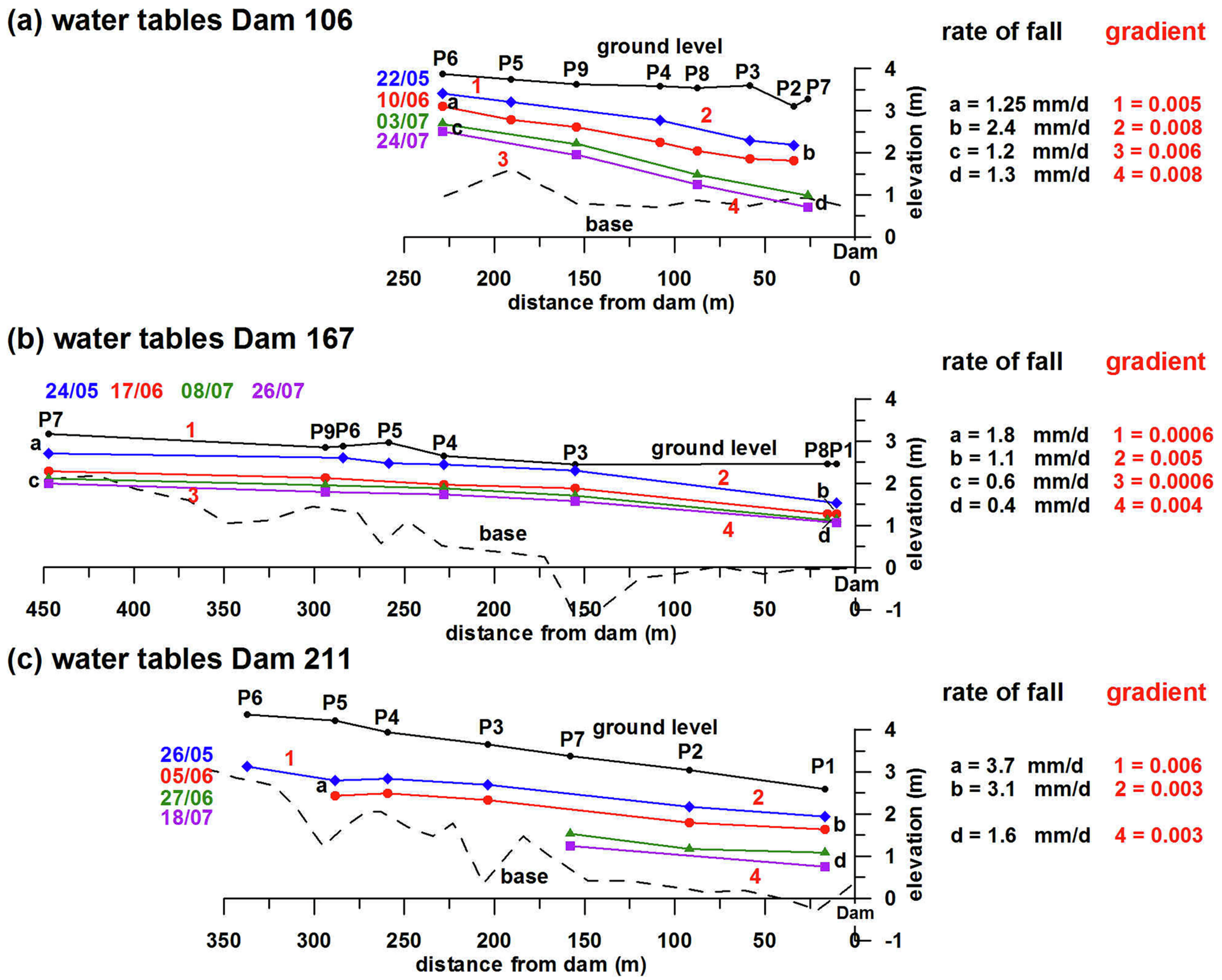


Fig. 4. Water table elevations in the deposited sand for each study area (P = piezometer). (a) Sand dam 106, (b) sand dam 167 and (c) sand dam 211. Letters a to d signify where the rate of fall in the water level is recorded; numbers 1–4 in red indicated where the slope in the water table is calculated. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.6. Aquifer properties estimated from pumping tests

The pumping tests were analysed using a two zone numerical model (Rushton, 2003); this approach was chosen because it allows the representation of inflow to the base of the well and the water stored in the well. Furthermore the model can include both the pumping and recovery phases in a single simulation. Full details of the tests are presented in Rushton (2018).

From the numerical model used to interpret the pumping tests the hydraulic conductivity of the sand deposits is estimated to be 27–31 m/d. The specific yield (drainable porosity) is lower than total porosity and applies when water drains from the deposits, but there is also an alternative specific yield for the upward movement of water due to evaporation; from lysimeter experiments in sand dams this alternative specific yield was calculated to be in the range 0.10–0.16 (Quinn et al., 2018a). Overall a specific yield of 0.13 is an appropriate value for medium sand, which takes into account the silt and clay contained in the deposits.

3.7. Evaporation

Unlike evaporation from open water, the magnitude of evaporation from bare soil decreases as the water table falls. Hellwig (1973b) describes long term experiments using deep lysimeters in a sand river bed in Namibia to estimate actual evaporation with the water table maintained at specified depths. The small evaporation with the water table at 60 cm has been used to justify the effectiveness of sand dams (Borst and de Haas, 2006; Maddrell and Neal, 2012). However, there have been no reliable experiments in sand dams to check the validity of this assumption. Therefore 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 with a piezometer installed in each lysimeter to record the fall in water level, results for the first test in Lysimeter 1, dam 167, are indicated by the crosses in Fig. 3(b).

Interpretation of the field results depends on estimates of the potential evaporation which are obtained using the method of Hargreaves which is based on estimates of the radiation and the maximum, minimum and mean temperatures (Hargreaves and Samani, 1985; Hargreaves and Allen, 2003). Hillel (1980) and Allen et al. (2005) identify three stages in evaporation from bare soil: Stage 1 an initial constant rate, Stage 2 an intermediate falling rate and Stage 3 a residual low rate stage; these stages are shown in the right hand diagram of Fig. 3(b). The water table depths over which these stages apply depends on the properties of the soil (Allen et al., 1998; Mutziger et al., 2005). Using a semi-empirical water balance model with the three stage relationship, the computed water table fall with time is plotted in

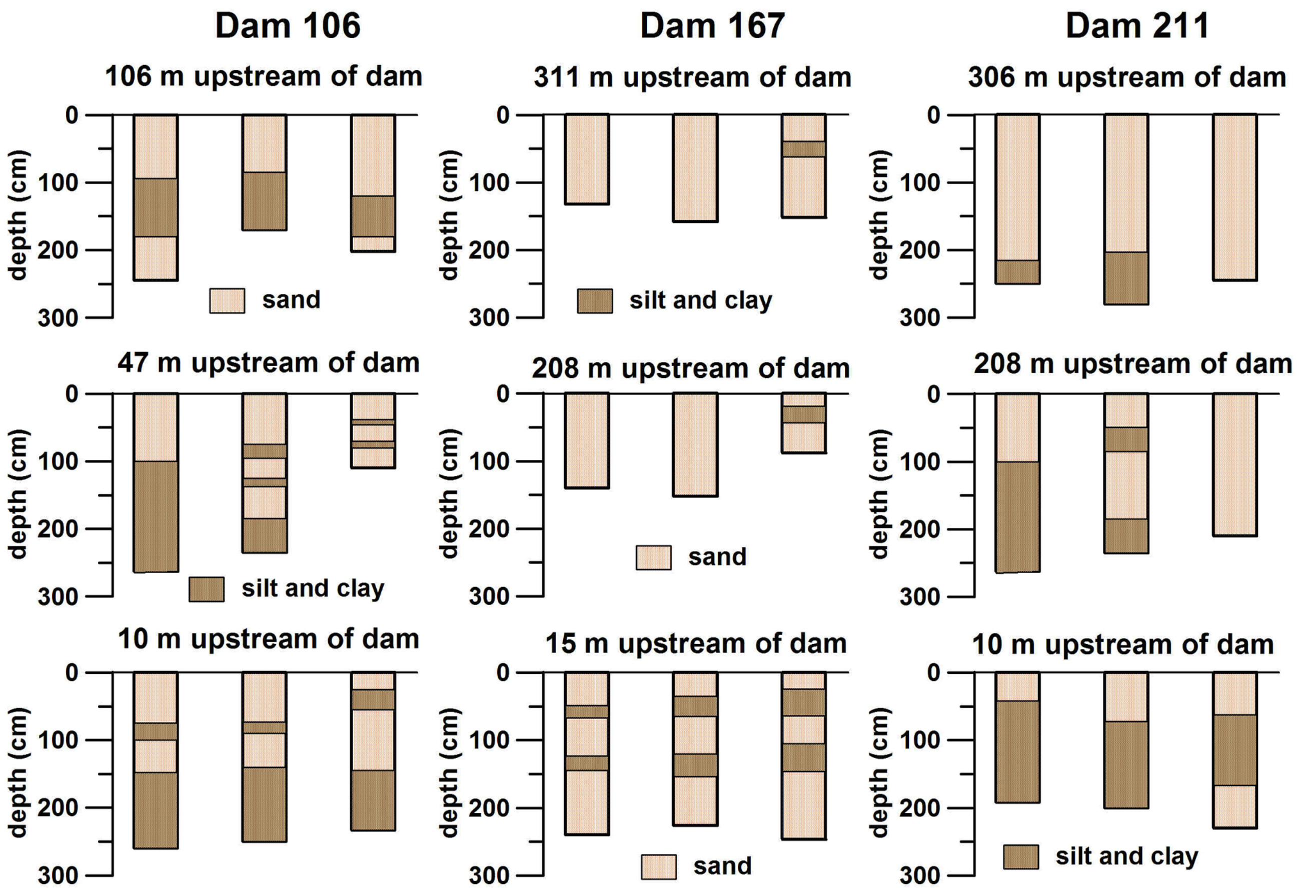


Fig. 5. Sediment profiles for each sand dam.

Table 2
Parameters used to Calculate Water Balance.

Dam	Hydraulic conductivity (m/day)	Specific yield	Evaporation (mm/day)			Abstraction from scoop-hole (m^3/day)
			Depth to water table			
			0–0.4 m	0.4 m–1.0 m	> 1.0 m	
106	13–40	0.13	6.0	6–1.0 (linearly decreasing)	1.0	N/A
167	15–30	0.13	6.0	6–1.0 (linearly decreasing)	1.0	0.6
211	15–30	0.13	4.5	4.5–0.75 (linearly decreasing)	0.75	0.4

Fig. 3(b); this is consistent with the lysimeter results. For more details see Quinn et al. (2018a). The values for the three stages for each sand dam are given in Table 2. Dam 211 has lower values because it sits in a deeper, shadier valley.

It should be noted that these relationships do not take into account the variation of stratigraphy with depth. Furthermore, Table 2 gives constant values for the potential evaporation whereas in reality this changes on a daily basis and also varies along the sand deposits in the sand dam due to features such as the presence of shade.

3.8. Water balance estimates

As an example, the water balance between two piezometers in Dam 106 (Section 3.8.1) is described, followed by the water balance for the whole of Dam 106 (Section 3.8.2). The water balances for Dam 167 and Dam 211 are included in the supplementary material. A summary of the parameter values used when calculating the water balance components for all three sand dams are given in Table 2, uncertainties about parameter values are considered in Section 3.10.

3.8.1. Details of a calculation for reach between P3 and P2 in Dam 106

To introduce the method of calculating a water balance, conditions between piezometers P3 and P2 during the time period 22nd May to 10th June are presented in Fig. 6.

Plan and cross-sectional areas of the saturated sand deposits are required to compute components of the water balance; the estimation of these areas is based on the topographical survey and probing to assess the depth of the sand deposits. The plan area, Ap (Fig. 6a) is estimated to be 296 m^2 and the cross sectional area of saturated sand (Fig. 6c) along the line of probing is 10.6 m^2. The quantified components of the water balance, Eq. (1), are as follows:

(i) S_R: water released from storage as water table falls. During a time period, Δt, of 19 days, the average fall in water table Δh was 0.48 m (Fig. 6c). As per Section 3.6, a value of 0.13 for specific yield, S_Y, is selected. Thus:
$S_R = \text{Ap} \times S_Y \times (\text{Dh}/\text{Dt}) = 1.0\,\text{m}^3/\text{d}$

(ii) *F:* lateral flow within a reach. This flow depends on the hydraulic gradient between P3 and P2 of 0.077 m over a distance of 22 m; the cross-sectional area is 10.6 m^2. The hydraulic conductivity in each

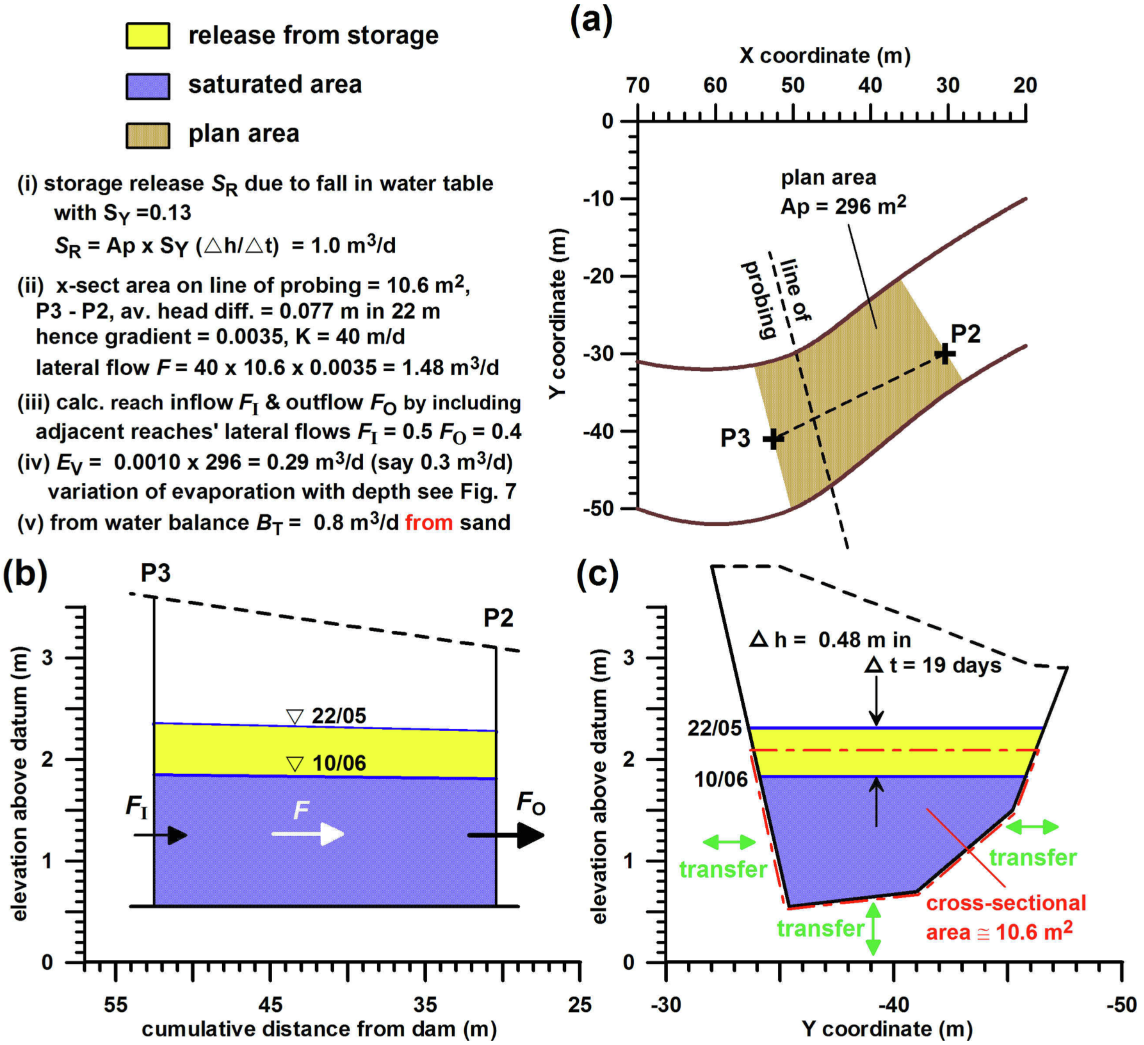


Fig. 6. Water Balance for the reach between P3 and P2 for Sand Dam 106 (a) plan view (b) vertical section between P3 and P2 (c) cross-section through the sand deposits.

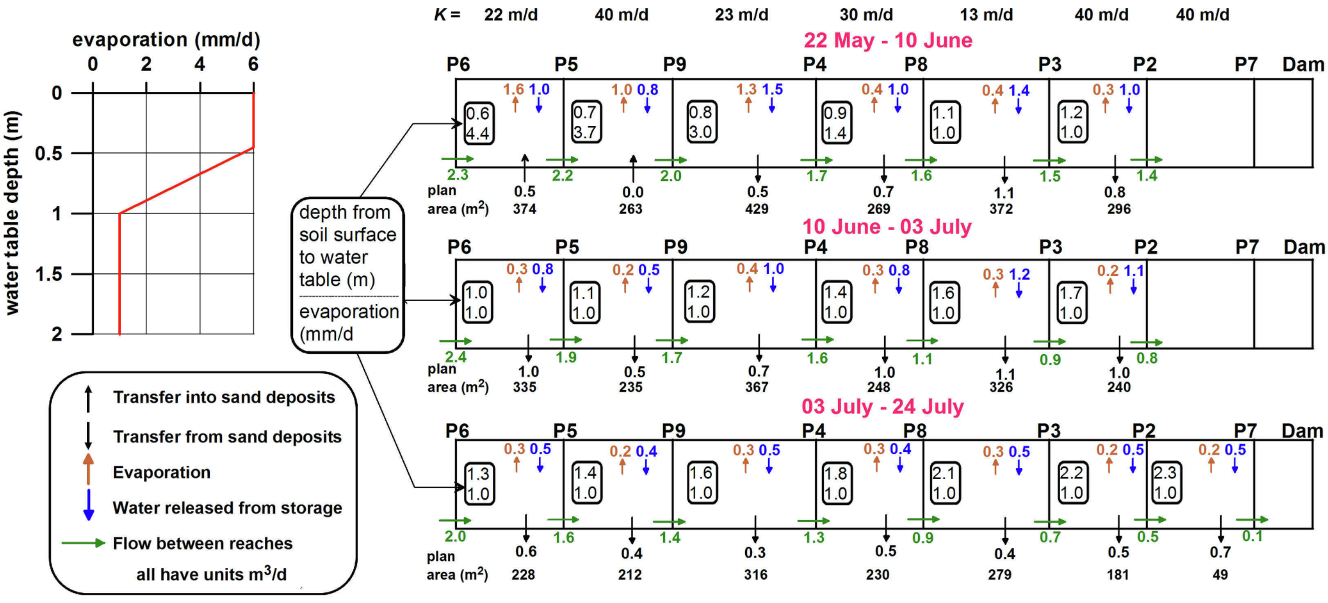


Fig. 7. Detailed water balance for Dam 106; variation of evaporation with depth shown in diagram on left.

reach needs to be selected so that the flows in the mid-point of each reach change steadily; also the hydraulic conductivity should not vary significantly from the values estimated during the pumping test (Section 3.6). The range of hydraulic conductivity values is given in Table 2. In the reach between P2 and P3 the hydraulic conductivity is taken as 40 m/d. Consequently

$$F = 10.6 \times 40 \times (0.077/22) = 1.48\,\mathrm{m}^3/\mathrm{d}$$

The inflows and outflows for the reach, F_I and F_O, depend on the flows in the current and adjacent reaches; hence, $F_I = 1.5\,\mathrm{m}^3/\mathrm{d}$, $F_O = 1.4\,\mathrm{m}^3/\mathrm{d}$, so that $F_I - F_O = 0.1\,\mathrm{m}^3/\mathrm{d}$.

(iii) E_V: evaporation from the sand surface. The depth to the water table is 1.2 m hence the evaporation takes the minimum value of 1.0 mm/d, as per Table 2.

$$E_V = \mathrm{Ap} \times 0.0010 = 0.30\,\mathrm{m}^3/\mathrm{d}$$

(iv) the abstraction Q_A is zero in this reach

Rearranging Eq. (1) allows the calculation of the transfer into or out of the sand deposits:

$$B_T = S_R + (F_I - F_O) - E_V - Q_A = 1.0 + 0.1 - 0.3 - 0 = 0.8\,\mathrm{m}^3/d$$

3.8.2. Full water balance for Dam 106

A detailed water balance for Dam 106, calculated using the method discussed above, is included in Fig. 7. The water balance is shown for three time intervals of approximately equal length.

Due to the significant clay deposits in Dam 106 the hydraulic conductivity is variable along the individual; values ranging from 13 to 40 m/d are used and the values for each reach are listed at the top of Fig. 7. Lateral inflows and outflows to a reach, F_I and F_O of the individual reaches are derived from the central and adjacent flows; they are indicated in green in Fig. 7.

The variation of evaporation with depth is plotted on the left of Fig. 7; the 'round cornered rectangles' in the main diagrams record the depth to the water table for each reach and the corresponding evaporation in mm/d. This evaporation is converted to the total evaporation for the reach by multiplying by the relevant plan area; the evaporation is recorded in Fig. 7 adjacent to the brown arrows.

The quantity of water released due to the fall in the water table is indicated by the blue arrows.

The transfer into or out of the sand deposits for each reach is estimated from Eq. (1). This transfer is recorded below each reach; an upward arrow indicates an inflow and a downward arrow an outflow.

Fig. 7 provides an overall representation of the flow processes associated with the sand deposits and how they change during a dry season. As the water table falls, cross-sectional and plan areas decrease leading to smaller values in the lateral flows F and the water released from storage SR. The evaporation EV reduces as the water table falls.

One objective in preparing water balances for individual reaches is to ascertain how the sand dam interacts with the adjacent material during a dry season. Apart from reaches P6-P5 and P5-P9 during the first time period, water is always lost from the sand deposits of Dam 106.

3.9. Significance of water balance results

To illustrate the significance of the water balance calculations, results are presented in Fig. 8 for selected reaches and at different times for each of the sand dams. Field evidence which confirms the estimated transfers is discussed. In Fig. 8 results are quoted both as L/d per unit length of the reach and as mm/d per unit plan area to assist in comparisons between the sand dams, the start and end of the time periods are given below the graphs.

3.9.1. Sand Dam 106

The reach considered in Dam 106, Fig. 8(a), is between piezometers P5 and P6 at the upstream limit of the monitoring. Note that between the early and late time periods there is a substantial reduction in evaporation from 42 to 6 L/d/m due to the increased depth to the water table. For the first time period early in the dry season the transfer is from the surrounding aquifer system into the sand deposits at 13 L/d/m; however, later in the dry season there is a transfer into the surrounding aquifer system of 18 L/d/m. This reversal of transfer flows is confirmed by the information in Fig. 9a which records the conductivity of the water at a number of locations from May to July. This conductivity record includes, as a red line, data from a deep open well into the friable mica schist valley side located about 200 m upstream of P6 (location indicated in Fig. 2a). Between late May and early June the conductivity was less than 1.1 mS/cm indicating relatively fresh water perched above saline water; whereas from mid-June and into July the conductivity increased to 2.2 mS/cm. Fig. 9(b) is a schematic diagram of conditions early in the dry season when the open well water level was initially close to the surface with fresh water due to rainfall entering the upper part of the well; fresh water also enters the sand deposits. However by mid-June onwards, the water level in this open well had fallen to lower than the bottom of the sand deposits and the conductivity in this well reflects the high conductivity of the bedrock water, as shown in right hand diagram of Fig. 9(b).

The quality of the water in the sand deposits is indicated by the blue line in Fig. 9a; it remains relatively low because, apart from recharge during the wet season, no water enters the sand from the surrounding aquifer system. The hand pump for Dam 106 is located between P2 and P3 in friable rock to one side of the sand deposits, as shown in plan view in Fig. 2a; in smaller sand dams hand pumps are often located in the rock on the valley sides just upstream of the dam. The quality of water from the hand pump remains relatively low as indicated by the black line in Fig. 9a; the pump abstracts water transferred out of the sand deposits. Downstream of the dam water is ponded; the conductivity, which is indicated by the green line, is between that of the sand deposits (piezometer) and that deep in the bedrock.

3.9.2. Sand Dam 167

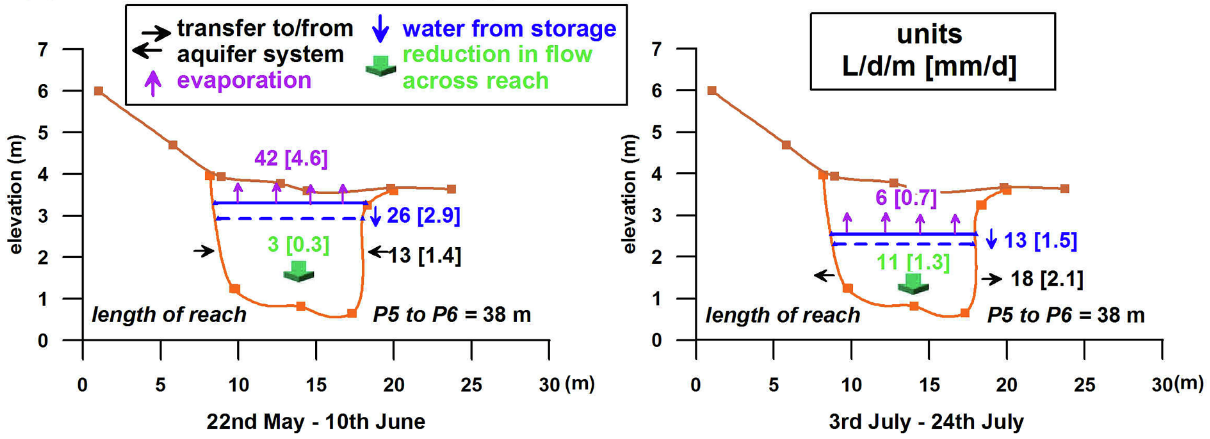
Dam 167 receives transfer flows from the surrounding aquifer system throughout the monitoring period; these are indicated in Fig. 8(b) for the reach between P4 and P5 as black arrows pointing towards the sand deposits. Even before the construction of the sand dam, it is known that fresh water was entering the valley as the scoop hole, has been present at the same location for forty years and has always provided good quality water (location of scoop hole indicated in Fig. 2(b)). Since the construction of the sand dam it has continued to be used; during the study period a detailed record was kept of the water collected from the scoophole on two occasions. At the start of the dry season 0.66 m^3/d of water was collected during a day; ten weeks later this reduced to 0.44 m^3/d. The valley bank above the scoophole is steep rising about 25 m in a lateral distance of 100 m; this is considered to be the source of the small steady inflow of fresh water to the sand deposits.

With this inflow of fresh water, less water is released from storage especially during the second time period 8th–26th July, consequently the rate of water table decline (see Fig. 4) is less than in Dams 106 and 211. Another important feature is that the flow through the sand deposits between reaches increases towards the dam (so the change is -5 and – 3 L/d/m in Fig. 8(b)), whereas for the other two sand dams, this flow decreases indicating losses from the sand deposits. A further finding is that the transfer flow into the sand deposits decreases over the monitoring period. This could be attributed to the decreasing wetted perimeter between the saturated deposited sand and the surrounding aquifer system.

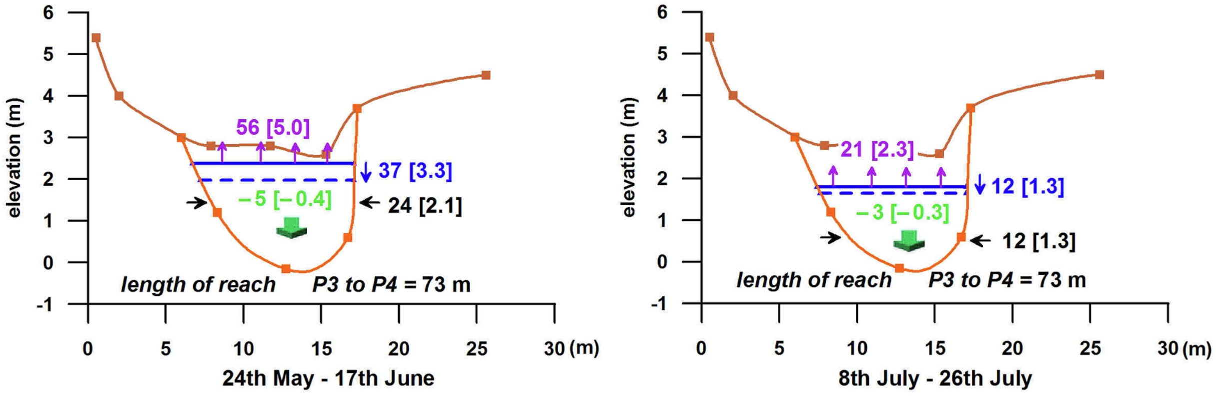
3.9.3. Sand Dam 211

There is a rapid fall in the water table in Dam 211 with the upper

(a) Dam 106 Section 1 between piezometers 5 and 6



(b) Dam 167 Section 1 between piezometers 3 and 4



(c) Dam 211 Section 2 (P4 - P5) and Section 1 (P1 - P2)

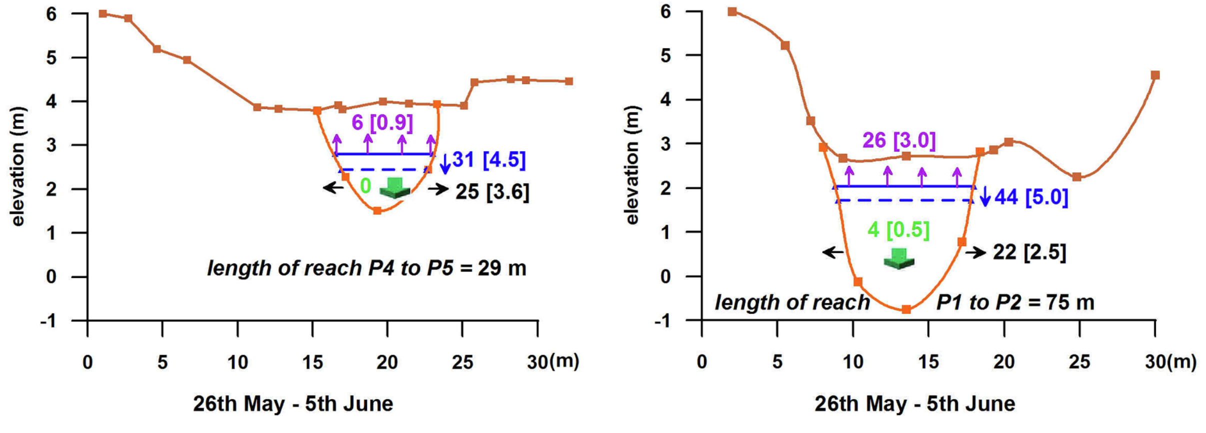


Fig. 8. Selected water balances for certain reaches (a) Dam 106 Section 1 between piezometer 5 and 6 (b) Sam 167 Section 1 between piezometer 3 and 4 (c) Dam 211 section 2 (P4–P5) and Section 1 (P1–P2); units L/d/m and [mm/d].

reaches becoming almost dry during the period of monitoring. Consequently Fig. 8(c) includes results for two different reaches both for the initial time interval, 26th May to 5th June. Water is transferred into the surrounding aquifer system for all reaches during all the time periods.

For Section 2; in the reach between P4 and P5, the saturated cross-sectional area is smaller than any of the other cross-sections on Fig. 8, yet the transfer is the highest of the six examples. This transfer is influenced by the presence of a large diameter agricultural well approximately 10 m from P5 (as shown in Fig. 2). The well was constructed several years before the sand dam was built and is still frequently used for irrigation. The water level at this well dropped below the base of the deposited sand within 4 weeks of the start of monitoring, indicating that water in the surrounding aquifer system was lower than the deposited sand, so that the deposited sand acts as a leaky perched aquifer. Interpretation of a pumping test in this large diameter well shows that water was collected from the overlying sand deposits and transmitted through the bedrock to the pumped well (Rushton, 2018). The transmissivity of the bedrock is estimated to be between 2 and 10 m2/d.

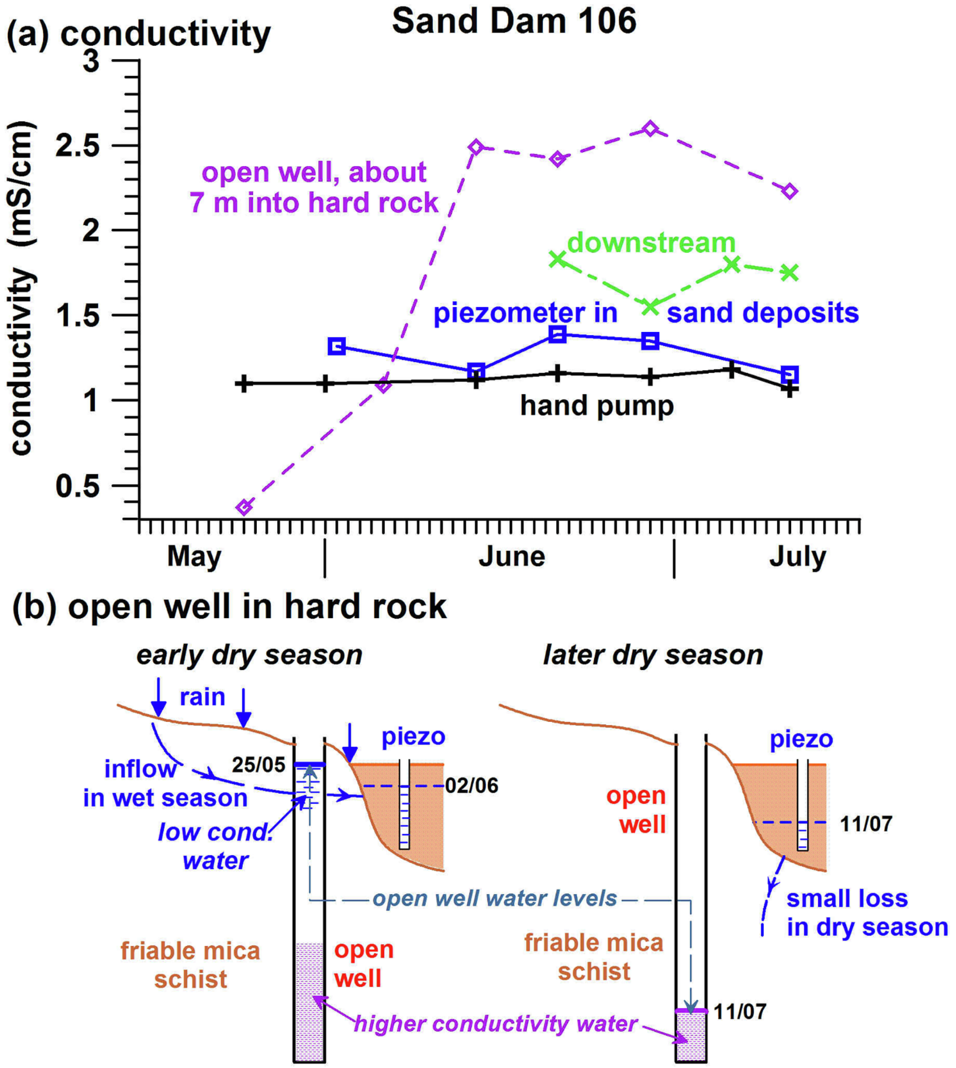


Fig. 9. Conductivity of water and flow paths in sand dam 106: (a) conductivity at various locations, (b) conditions in an open well adjacent to sand deposits.

Section 1 is located about 30 m from the dam wall; the flow processes are similar at the hand pump. The water released from storage is the highest of the six examples in Fig. 8. However with the rapid fall in the water table as the dry season progresses and the substantial decrease in the wetted perimeter, the transfer of water from the sand dam to the surrounding aquifer system for the third time period was only 40% of that for the first time period (as shown in the supplementary material). Consequently, although for the early stages of the dry season the conductivity of the water from the hand pump was 1.7 mS/cm, it increased to 3 mS/cm later in the dry season.

3.10. Sensitivity analysis for water balance calculations

Table 3 illustrates the impact of alternative parameter values on the magnitude of the transfer B_T; values in Row 1 are taken from Fig. 7. Row 2 of the table shows that reducing the hydraulic conductivity to two-thirds of the original value has a negligible effect with only two reaches taking different values for the transfer. Decreasing the maximum evaporation, Row 3, from 6 to 5 mm/d results in increases in the transfer B_T from the sand deposits to the surrounding aquifer system; nevertheless, for reach P6–P5 water continues to enter the sand deposits although at a reduced rate. If no evaporation is allowed when the water table is below 1.0 m, Row 4, there is no substantial change in

Table 3
Values of the transfer B_T from the sand deposits to the surrounding aquifer system (units m^3/d) for changed parameter values: results for Dam 106 between 22nd May and 10th June.

		B_T value for each reach in m^3/d					
Row number	Changed parameter	P6–P5	P5–P9	P9–P4	P4–P8	P8–P3	P3–P2
1	Original	−0.5	0.0	+0.5	+0.7	+1.1	+0.7
2	Reduce hydraulic conductivity to 2/3 of original	−0.5	−0.1	+0.4	+0.7	+1.1	+0.7
3	Decrease maximum evaporation from 6 to 5 mm/d	−0.2	+0.2	+0.7	+0.8	+1.2	+0.8
4	Set TAW to zero at a water table depth of 1.0 m	−0.4	+0.2	+0.9	+1.0	+1.5	+1.0
5	Increase S_Y from 0.13 to 0.26	+0.5	+0.8	+2.0	+1.7	+2.5	+1.7

transfers from the original situation. Substantial differences from the original transfer values are recorded in Row 5 when the specific yield is doubled; this leads to significant increases in B_T from the sand deposits to the surrounding aquifers. The transfer in the reach P6–P5 is reversed from an inflow to an outflow; this is not consistent with the observed water levels in the open well adjacent to the sand deposits, Fig. 9(b). Consequently the higher values of the specific yield of 0.25–0.30, frequently quoted for sand dams, are not supported by this study; the original value of 0.13 is consistent with the pumping test results as discussed in Section 3.6.

4. Discussion

Check dams are designed to store most of the runoff from the catchment above the dam site, although they lose up to 30% of that through evaporation (Dashora et al., 2018). Sand dams are experience less evaporation as it reduces as the water table falls further below the ground surface.

They are only expected to store a small proportion of the runoff (Maddrell and Neal, 2012) so that water is available downstream. Other important features are that check dams are intended solely to enhance recharge to the underlying aquifer system, whereas sand dams are usually intended for local use with water from the sand deposits available throughout a dry season. The three studied sand dams performed very differently as the dry season progressed. Dam 167 had the most water still available for abstraction, principally because it receives water transferred from the surrounding aquifer system. Dams 106 and 211 consistently leak water into the surrounding aquifer system (apart from the first month of the dry season in the upper reaches of Dam 106). Despite the leakages, the communities around all three sand dams realised benefits from dam construction, by abstracting water from the hand pump (constructed on a hand dug well into the surrounding aquifer system), from scoop holes constructed into the river bed, from other wide diameter wells near to the sand dam and even from the water that ponded at the base of Dams 106 and 167 which is used for watering livestock, fish culture, brick making, laundry and irrigation. There will be other benefits which are harder to quantify as the water that leaks will ultimately be recharging the surrounding aquifer system which are widely used in the region as a water source, not just in the immediate vicinity of the sand dams. So it could be useful to start defining sand dams as “managed aquifer recharge” structures, rather than thinking of them as isolated storage units, and starting to quantify the benefits of sand dams accordingly. The assumption of Hoogmoed (2007), Hut et al (2008) and Quilis et al. (2009) that the bed of a sand dam is impermeable seems not to be true. Maddrell and Neal (2012) recommend sealing any cracks in the bed with concrete before dam construction. There are no records as to whether this was done for these three dams but it seems to have not been effective.

It would be ideal to be able to identify in advance sites that will behave more like Dam 167 than Dam 211. However this study reveals nothing beyond the existing advice of RAIN (2002) and Maddrell and Neal (2012).

5. Conclusions

From the water balances performed in reaches between the piezometers it is clear that each of the sand dams performs differently due to their unique relationship with the surrounding aquifer system. Dam 106 gains water at the start of the dry season upstream then subsequently loses it, Dam 167 gains water throughout the study period and Dam 211 consistently loses water. The effect this has on the ability of the dams to supply and store water is also clear with Dam 211 becoming dry and the water levels in Dam 106 decreasing substantially over the monitoring period. However in all cases the community benefit from the additional storage created by the dams for at least partway through the dry season regardless of their leakage.

A reliable estimate of the specific yield is crucial when assessing the potential water resource of a sand dam. Much of the sand dam literature suggests values of 0.30 or higher. These estimates are appropriate if the sand dam deposits are well-sorted. For these sand dams, the deposits were found to be poorly sorted so that the specific yield is assumed to take a value of 0.13. This indicates that the volume of water actually stored in the sand deposits is less than conventionally assumed.

During the planning of the fieldwork for the sand dams, the significance of the transfer from the sand deposits to or from the surrounding aquifer systems had not been recognised; in future studies extensive data should be collected both in the sand deposits and in the surrounding aquifers.

The water balance presented in this paper is a valuable first step in understanding the hydrology of sand dams. Although the field study only covered part of a single dry season, sufficient data were obtained to develop a conceptual understanding of the important flow processes and obtain preliminary estimates of the flow components. A further stage is to prepare computational models of these systems so that the impact of changing dam design parameters can be examined.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.hydroa.2019.100035.

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