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Collection and storage of runoff from hillslopes in a semi-arid environment: geomorphic and hydrologic aspects of the aljibe system in Almeria Province, Spain

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Water harvesting systems in south-east Spain collect runoff from hillslopes in underground cisterns (aljibes). The characteristics of 51 aljibes were recorded. Aljibe volume increases non-linearly with catchment area ($r^2 = 0{\cdot}29$; $N = 51$). This relationship becomes even stronger for the water harvesting systems on rocky slopes ($r^2 = 0{\cdot}56$; $N = 34$). An empirical rainfall/runoff model indicates that the surface characteristics of the catchments are critical in producing sufficient runoff during years with low annual rainfall. The aljibe system is still viable provided the runoff coefficient of the catchments is high (curve number > 90) and the volume of the aljibes is large enough to prevent overflow (volume to catchment area ratio > 60 m^3 ha^{-1}).

Keywords: water harvesting; runoff; semi-arid hillslopes; runoff curve numbers; south-east Spain

Introduction

A variety of systems have been developed to provide supplementary water for rain-fed agriculture in semi-arid and arid regions (e.g. Yair, 1983; Giraldez *et al.*, 1988; Tabor, 1995; Lavee *et al.*, 1997). Water harvesting systems that collect runoff in underground cisterns to provide the needs of families and their livestock are common in Spain (Chapman, 1978; Cara Barrionuevo & Rodríguez López, 1989; Cara Barrionuevo, 1996), northern Africa (Claude & Bourges, in press), as well as in arid and semi-arid regions of India (Samra *et al.*, 1996, p. 102). There are indications that some forms of water harvesting systems were already used in Spain during the Bronze age (Chapman, 1978). Water collection cisterns (aljibes), similar to the ones found at present in Spain and northern Africa, were probably introduced to Spain during the Moorish period (12th century AD; Cara Barrionuevo & Rodríguez López, 1989). Apart from water harvesting systems in urban areas that collect water from roof tops and terraces, catchments on hillslopes are used in rural areas to collect runoff water. It is the geomorphic and hydrologic characteristics of the latter system that is poorly described in the literature and that will be discussed in this paper.

Rainfall in (semi)-arid regions produces a discontinuous runoff that in many cases never reaches the valley bottom (Yair, 1983; Lavee & Yair, 1990; Brown & Dunkerley, 1996; Nicolau *et al.*, 1996; Lavee *et al.*, 1997). Therefore, suitable sites where runoff is produced even during light rains are limited and relatively small. Yair (1983), Lavee & Yair (1990) and Lavee *et al.* (1997) have shown that, above all, rock outcrops produce runoff which tends to infiltrate further downslope in the colluvial mantle. These rock outcrops and thin, stony soils show a spatial distribution that depends on the topography and land use (Poesen *et al.*, in press). Since ancient water harvesting systems have been modified and improved over centuries, these systems are concentrated in those zones in the landscape where runoff is produced most rapidly. A large sample of these cisterns with their catchments should therefore give insight into the best locations to generate runoff and the amount of runoff to be expected from a given surface. Hence an inventory of these cisterns and their catchments in Almeria province was carried out in order to investigate the geomorphic properties of this water harvesting system.

The large investments made in the construction and maintenance of aljibes suggests that these systems produce a reliable water source even in an area with a great temporal variability in rainfall. In the past, these aljibes, together with ponds and wells, were the only sources of drinking water for livestock, and as such their water consumption (based on size of the herds) was registered in archives (Cara Barrionuevo, 1996). Unfortunately, no data on the water supply to the aljibes are available. Therefore, water supply in the form of runoff was estimated according to the size and surface characteristics of the catchments using an empirical rainfall/runoff model based on rainfall records of nearby meteorological stations (the runoff curve number technique; Soil Conservation Service, 1986; Tragsatec, 1994). This type of research is all the more urgent since many of the 200–300 aljibes still present in Almeria province have now been abandoned and destroyed (Cara Barrionuevo, 1996). In the case of Almeria Province, rapid development of horticulture in greenhouses which rely on fossil ground-water has led to a decline of indigenous water harvesting systems in more accessible areas (Tout, 1990). However, similar water harvesting techniques can still contribute to the sustainable development of other regions (Le Houérou, 1996).

Materials and methods

Study area

The landscape of Almeria province (south-east Spain) is characterized by a basin and range topography. The mountain ranges are part of the Betic system consisting of a variety of parent materials: mica-schist in the Sierra de los Filabres, dolomite in the Sierra de Gador and andesite in the Sierra de Gata (Fig. 1). The intramontane basins, with extensive alluvial fan systems on the fringes, were developed in the Tertiary and early Quaternary epochs. These alluvial fans are often characterized by a calcrete in the upper part of the soil profile and are now dissected by the modern drainage network

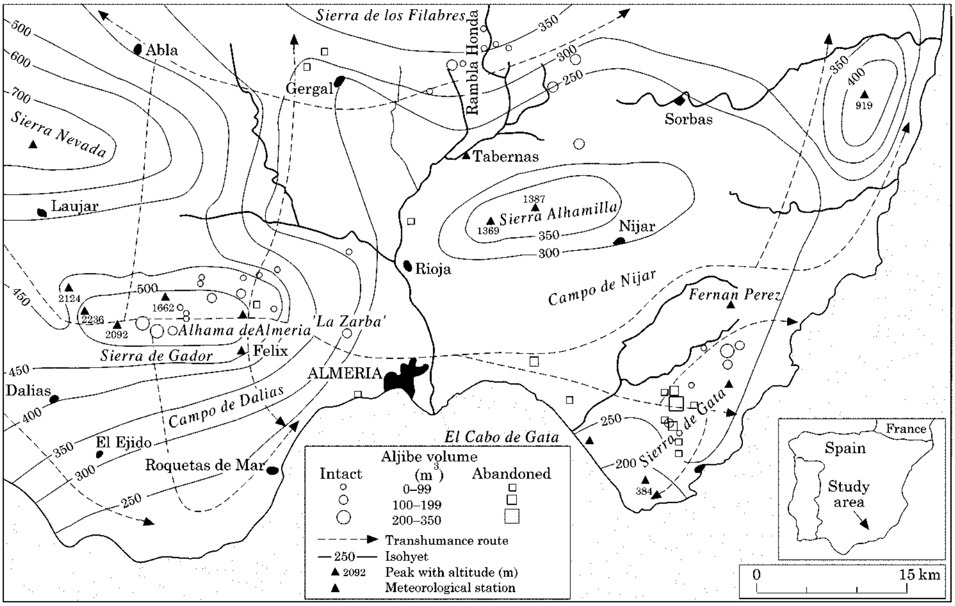

Figure 1. Distribution of the aljibes surveyed in Almeria province, also showing the transhumance routes (after Cara Barrionuevo & Rodríguez López, 1989) and the rainfall distribution (after Molina, 1977).

(Harvey, 1987). The largest part of Almeria province has a semi-arid climate with strong gradients in annual rainfall (P) and temperature (T): $P = 150$ mm and $T = 17–18$°C at the south-eastern coast (Cabo de Gata); $P = 650–700$ mm and $T = 8–9$°C on the summits of the Sierra de Gador (Fig. 1; Lázaro & Rey, 1991).

As a result of centuries of agricultural and mining activity in a fragile environment, vegetative cover in the largest part of Almeria province is sparse (Chapman, 1978). The forests in the mountain ranges were decimated by wood consumption of local mines and by grazing of flocks of sheep and goats. Grazing pressure in the mountains increases in summer when the flocks are transferred from their winter pasture in the plains to the summer pasture in the mountains (transhumance; Cara Barrionuevo, 1996). The plains and footslopes were used for rain-fed agriculture and grazing until the 1960s. Harvesting of flood water from ephemeral streams or ground-water in the sedimentary body of the larger rivers supplemented rainfall in narrow zones along the valley bottoms (Giraldez *et al.*, 1988). Nowadays, mining has stopped and emigration of the farmers has lead to progressive abandonment of arable land in the more remote areas. The vegetation ranges from pine forests in the mountains, to open shrubland and gramineous steppes on the little disturbed hillslopes, to chamaephytic steppes on the heavily grazed alluvial fans. The use of ground-water from aquifers has enabled a rapid development of greenhouses in the coastal plains to the west and east of Almeria (e.g. Campo de Dalias and Campo de Nijar; Tout, 1990).

Inventory of the aljibes

The aljibes are generally rectangular basins lined with walls of masonry and sunk to a depth of 2–3 m in gentle hillslopes (Fig. 2). The cisterns are covered with a

Figure 2. Position of a large aljibe (314 m^3) with a catchment on a steep hillslope in the Sierra de Gata. Note the runoff conduits at the base of the hill leading runoff to the aljibe and the sediment cleared from the aljibe.

dome-shaped roof of stone in order to prevent evaporation. Since the water was mainly used for animal consumption, the thick stone roof also served to keep temperatures low in order to maintain a reasonable water quality over a prolonged period (Cara Barrionuevo & Rodríguez López, 1989). They either fill directly with runoff water from the hillslope above them or with flood water from an ephemeral stream via a small channel. Apart from the water use for animal consumption, the water of some aljibes is also used for other purposes: domestic consumption for isolated farms, forest management (planting and fighting forest fires) and industrial processes related to mining.

Topographical maps and local information enabled us to locate 51 aljibes with their catchment which served as the source of runoff water. The study of the aljibes was concentrated in three areas: southern slopes of the Sierra de los Filabres, the Sierra de Gador, and the Sierra de Gata (Fig. 1). For each aljibe with its associated catchment the following parameters were measured or assessed in the field: general physiography of the catchment and land use; size of the catchment (m^2); slope of the catchment (%); condition of the soil surface: rock outcrop and rock fragment cover (%), vegetation cover (%), presence of a soil crust (%); volume of the aljibe (m^3); and condition of the aljibe (intact or abandoned).

Determination of the catchment area and the distinction between functioning and abandoned aljibes was facilitated by strong rains in the week prior to the survey. The runoff had left flow traces on the soil surface and had filled the aljibes that are still intact.

Hydrologic properties of the catchments

Daily precipitation data recorded in five nearby stations have been used (Fig. 1): Alhama de Almeria, La Zarba (1219 m a.s.l.) from 1961 to 1994; Felix (812 m a.s.l.) from 1964 to 1994; Tabernas (490 m a.s.l.) from 1965 to 1986; Fernan Perez (200 m a.s.l.) from 1963 to 1986; Cabo de Gata, Michelin (50 m a.s.l.) from 1973 to 1990.

The time series of annual precipitation were analysed using the standard anomaly

Table 1. (a) *Runoff curve numbers for different catchment surfaces under average antecedent moisture conditions (CN(II); Soil Conservation Service, 1986)*

		Curve numbers for hydrologic soil group		
Land use or cover	Hydrological condition	B (coarse textured valley bottom)	C (thin, rocky soils)	D (sealed surfaces)
Fallow	poor	86	91	94
Small grain	poor	76	84	88
Semi-arid pasture or rangeland	$< 30\%$ cover	80	87	89
	30–70% cover	71	81	89
	$> 70\%$ cover	62	74	85
Dirt roads		90	90	90

Table 1. (b) *Antecedent moisture conditions for Spanish rangelands (Tragsatec, 1994)*

	Rainfall in the preceding 5 days (mm)	
Antecedent moisture conditions	October–March	April–September
CN(I)	$< 12{\cdot}5$	$< 35{\cdot}5$
CN(II)	12·5–28	35·5–53
CN(III)	> 28	> 53

index (SAI) for the data of the above-mentioned stations (Eqn 1; Nicholson, 1983).

$$\mathrm{SAI} = 1/N \sum_{i=1}^{N} (\tau_{ij} - \mu_i)/\delta_i \qquad \text{(Eqn)1}$$

where N = number of stations, τ = raw station value, μ = reference period mean, δ = reference period standard deviation, i = individual stations and j = time step.

Given the lack of water supply data, the runoff collected in aljibes on rocky hillslopes was estimated by means of an empirical rainfall/runoff model based on surface characteristics of the catchments (0·1–13 ha) and daily rainfall of nearby meteorological stations. The runoff curve number method (CN) was used to estimate runoff from the catchments (Soil Conservation Service, 1986). The runoff curve number method is well suited to estimate runoff from small catchments using 24-h rainfall data (Haan *et al.*, 1994; Tragsatec, 1994). Curve numbers for the entire catchment of an aljibe were calculated by an area-weighting of the curve numbers of particular land use or cover (Table 1(a)). A correction for impervious surfaces such as rock outcrops was made using the nomograms published by the Soil Conservation Service (1986). Runoff (Q, mm) from selected catchments on rocky hillslopes was calculated for each rainy day (P, mm) using the curve number (CN) according to Eqns (2) and (3) (Haan *et al.*, 1994):

$$Q = \frac{(P - 0{\cdot}2S)^2}{P + 0{\cdot}8S} \quad \text{for } P > 0{\cdot}2S \qquad \text{(Eqn 2)}$$

$$S = \frac{25400}{\mathrm{CN}} - 254 \qquad \text{(Eqn 3)}$$

where S (mm) is the potential maximum retention after runoff begins. The runoff curve number method indirectly takes the intensity of the rainfall into account: (i) a certain amount of the rainfall ($0{\cdot}2S$ in Eqn (2)) is allowed to infiltrate or is retained in soil surface depressions, where S varies with the curve number (Eqn 3); (ii) the non-linear character of Eqn (2) reflects the increase in effective collective areas within the catchment with increasing rainfall. The weighted curve numbers of the catchments during average soil moisture conditions (CN(II)) were adjusted for very dry conditions (CN(I)) or wet conditions (CN(III)) using Eqns (4) and (5) (Haan *et al.*, 1994; Tragsatec, 1997; Table 1(b)).

$$\mathrm{CN(I)} = \frac{4{\cdot}2\mathrm{CN(II)}}{10 - 0{\cdot}058\mathrm{CN(II)}} \qquad \text{(Eqn 4)}$$

$$\mathrm{CN(III)} = \frac{23\mathrm{CN(II)}}{10 + 0{\cdot}13\mathrm{CN(II)}} \qquad \text{(Eqn 5)}$$

Results and discussion

Spatial distribution of the aljibes

The aljibes are concentrated in three main areas: Sierra de Gador, southern slopes of the Sierra de los Filabres and Sierra de Gata (Fig. 1). This nested distribution of aljibes does not necessarily reflect the spatial distribution of all (remains of) aljibes. Cara Barrionuevo (1996) reported the existence of some 250 aljibes in Almeria province, 51 of which have been sampled and surveyed in this study. Since we concentrated on the geomorphic position of the aljibes and their hydrology, only aljibes with a clear recognizable catchment were selected. Although some 20 aljibes still exist in the Campo de Dalias, their catchments have been destroyed by the development of greenhouses over the last decades in the coastal plains. Therefore, our survey was limited to the more remote areas and to the mountain ranges where aljibes are still functioning as the only source of accessible water.

The capacity of the aljibes varies between 12 and 314 m^3 with an average of 94 m^3. This variation in capacity reflects, on the one hand, differences in water consumption and, on the other hand, differences in the location of aljibes in the landscape regarding their possibility to frequently collect substantial runoff volumes. The largest aljibes (200–300 m^3) are nearly all located along the transhumance routes that connect the summer grazing in the Sierra de Gador, Sierra Nevada and Sierra de los Filabres with the winter grazing on the footslopes and in the coastal plains (Figs 1 and 2). These isolated aljibes, dating back from at least the 18th century, were distributed in such a manner that they served up to 1500 ha of pasture belonging to several villages (Cara Barrionuevo & Rodríguez López, 1989). Nowadays, many of the large aljibes and those far away from an aquifer in the Sierra de Gador and the Sierra de los Filabres are still in use (Fig. 1). The small aljibes close to farms in the coastal plains are often abandoned and replaced by deep wells.

In order to maximize the efficiency of the aljibes, the catchment has to be located in zones with a nearly impervious surface which generates runoff even after light rainfall. The aljibes in this survey ($N = 51$) received their runoff water from one of the following types of catchments: hillslopes with a large percentage of rock outcrops and thin soils often bordered with runoff conduits to prevent infiltration in the colluvial soils further downslope (Fig. 2; $N = 34$); a sloping dirt road and its shoulders often channelled through drains to the aljibe ($N = 8$); gently sloping alluvial fans with a bare, sealed surface on top of a loamy soil ($N = 6$); and headwaters of ephemeral streams by means of flood water diversion structures (i.e. boqueras; Giraldez *et al.*, 1988) ($N = 3$).

Efficiency of the catchments

The most important characteristic of the catchments is their ability to produce runoff even during light rainfall. At each aljibe the size of such catchments is limited by the topography, or the presence of a colluvial mantle, favouring infiltration, further down the slope. The significant positive relation between catchment area and volume of the aljibe ($R^2 = 0{\cdot}29$; $N = 51$) indicates that the catchments were dimensioned in order to maximize runoff collection during rains occurring at least once a year (Fig. 3). The non-linear character of this relationship suggests efficiency of runoff generation decreases with increasing catchment area. This observation is confirmed by both laboratory and field experiments. Poesen & Bryan (1989) concluded from both the literature and their own laboratory experiments in flumes of different lengths that the efficiency of runoff generation decreases with slope length due to the occurrence of erosion and sedimentation processes along the slope that can enhance infiltration. Experiments conducted by Yair (1983) and Lavee & Yair (1990) in the Negev showed that during simulated rainfall with an intensity of 26 mm h^{-1} steep slopes with a large percentage of rock outcrop produced runoff which infiltrated in the colluvial mantle downslope and thus never reached the ephemeral stream in the valley. A similar observation was made by Nicolau *et al.* (1996). Runoff plots on steep slopes with thin soils on mica-schist in the Rambla Honda catchment (southern slopes of the Sierra de los Filabres; Fig. 1) produced runoff with daily rainfall of 10 mm, whereas the occurrence of runoff in plots on the sedimentary body on the footslopes was very rare.

The catchments on hillslopes ($N = 34$) are generally rocky with thin soils. The mean percentage of rock outcrop in these catchments varies between 29% in the Sierra de Gador, 48% in the Sierra de Gata and 50% in the Sierra de los Filabres. The clearly

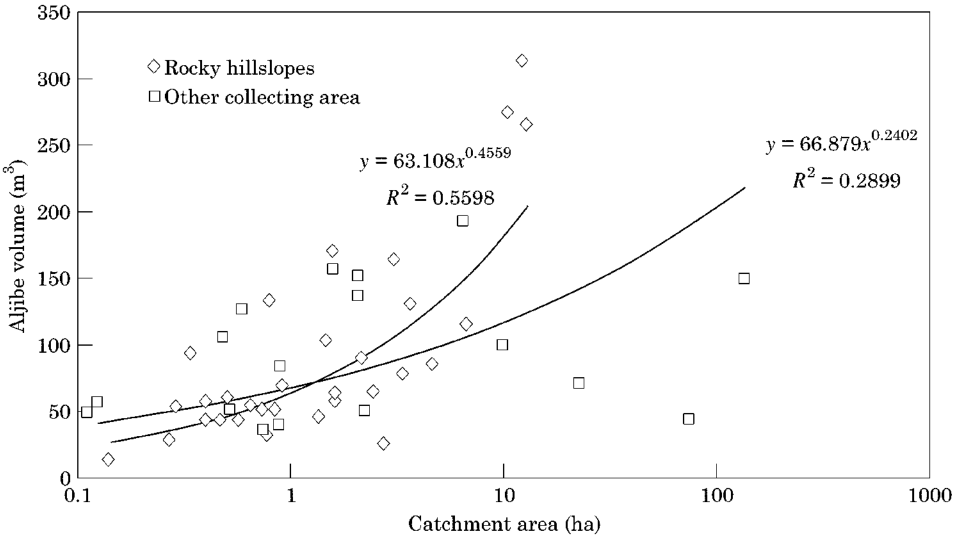

Figure 3. Relationship between catchment area and aljibe volume. The graph shows regression lines for all aljibes ($N = 51$) and for those on rocky hillslopes ($N = 34$).

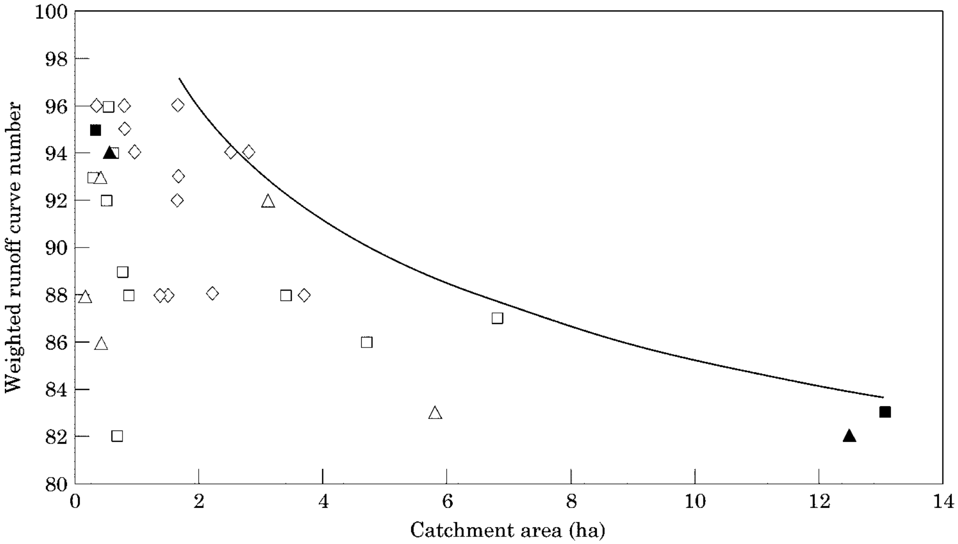

Figure 4. Relationship between catchment area and weighted runoff curve number (CN(II)). (◇) = Sierra de los Filabres; (□) = Sierra de Gador; (△) = Sierra de Gata. Closed symbols indicate the catchments that are examined in Fig. 5.

lower percentage of rock outcrop in the Sierra de Gador is a result of denser vegetation cover leading to a better protection of the soil in this more humid area (Fig. 1). The increase of the volume of the aljibes with increasing catchment area becomes stronger and more significant ($R^2 = 0{\cdot}56$) when only the aljibes on hillslopes with thin rocky soils are considered ($N = 34$; Fig. 3). Due to the limited extent of rock outcrops and slopes with thin soils which produce runoff very quickly, the envelope of runoff curve number *vs*. catchment area shows a declining trend (Fig. 4). This relationship shows that the runoff coefficient on these rocky slopes is very high and that these rocky slopes were above all selected as catchments for the aljibes. Some aljibes are even fed by catchments where the bedrock has been artificially removed.

Relation between rainfall and runoff

The variability of rainfall between years is large, judging from the records of five stations in Almeria province from the early 1960s to the late 1980s. Although it is difficult to predict any long-term trends from records of little over 20 years, there is a clear distinction between a wet period prior to 1976 and a dry period from 1976 onwards (Fig. 5(a)). This trend fits a gradual decrease in precipitation since 1950 for the western Mediterranean basin (Palutikof *et al.*, 1996). The variability in annual rainfall is only a very crude indicator for the production of sufficient runoff to fill the aljibes at regular intervals, since only runoff-producing rainfall is relevant and the occurrence of dry spells between such events is of vital importance.

Four water harvesting systems with different aljibe volumes and catchment areas (closed symbols in Fig. 4) have been selected in order to test the sensitivity of runoff generation to the runoff curve number of the catchment. The annual runoff was calculated using Eqns (2) and (3) based on daily rainfall records of Alhama de Almeria ‘La Zarba’ (Sierra de Gador; mean annual rainfall of 422 mm) and Fernan Perez (Sierra de Gata; mean annual rainfall of 247 mm). Differences in runoff response of

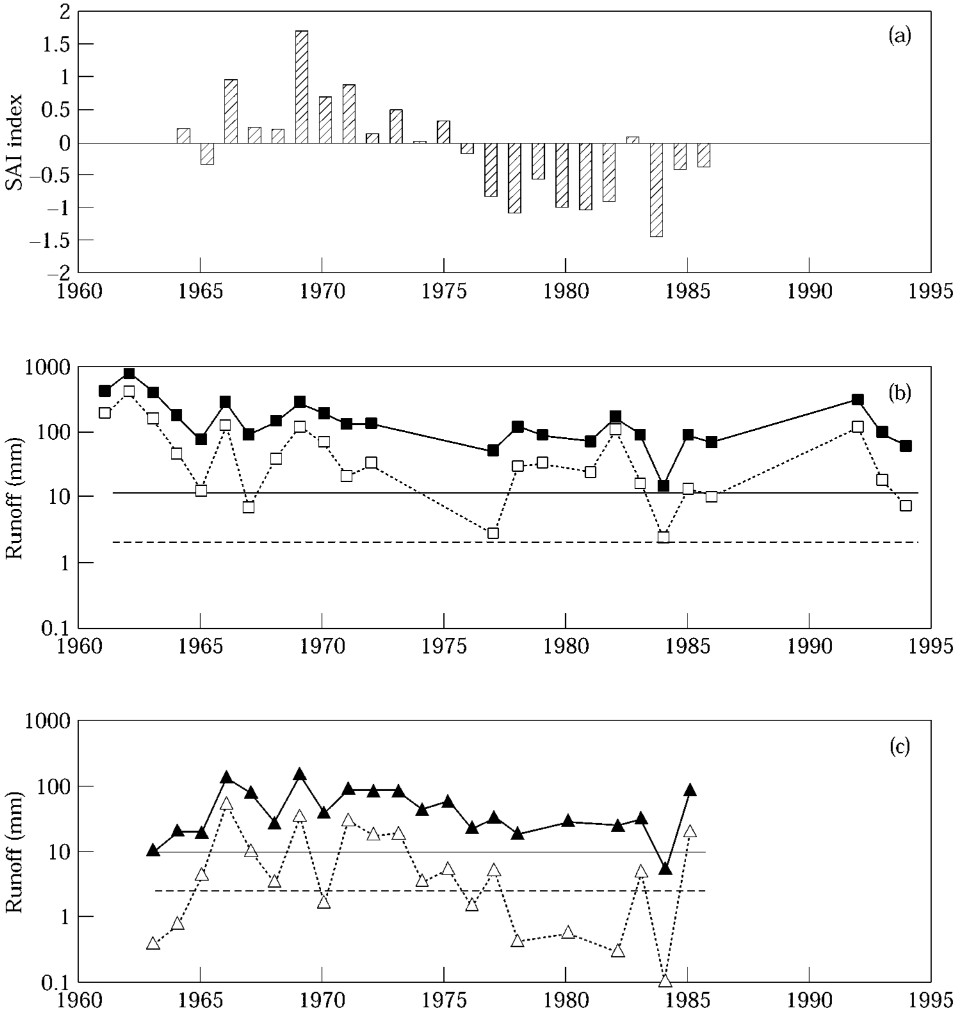

Figure 5. Annual trends in rainfall and runoff from four selected catchments (closed symbols in Fig. 4). (a) Standard anomaly index (SAI) of annual rainfall; (b) runoff from catchments in the Sierra de Gador with high, CN(II) = 95 (—■—), and low, CN(II) = 83 (- -□- -) runoff curve numbers. The amount of runoff that will fill the corresponding aljibes is indicated by the horizontal solid and dashed lines, respectively; and (c) runoff from catchments in the Sierra de Gata with CN(II) = 94 (—▲—) and CN(II) = 83 (- -△- -).

individual rainfall days as a result of variations in antecedent soil moisture conditions were also taken into account (Eqns (4) and (5); Haan *et al*., 1994). The runoff depth required to fill the aljibes connected to these catchments are represented by the horizontal lines in Fig. 5. Although the annual runoff of catchments with a high runoff curve number (CN(II) $>$ 90) produce the largest annual runoff, their limited size (mainly restricted to rock outcrops; Fig. 4) implies that aljibes collecting runoff from these small catchments will require a considerable runoff depth to fill ($>$ 10 mm). Larger less efficient catchments (CN(II) $<$ 90) yield lower annual runoff depths, but the aljibes connected to such large catchments will require less runoff depth to fill ($<$ 3·5 mm). The aljibes in the Sierra de Gador are the most reliable ones: they will be replenished at least once a year, even in 1984 when the annual rainfall fell to 158 mm

(Fig. 5). In the Sierra de Gata, the choice of the location of the catchment appears to be vital (Fig. 5). Catchments with a high runoff curve number (CN(II) = 94) will generate at least 10 mm of runoff per year, apart from the extremely dry year of 1984 with only 92·5 mm rainfall. However, the aljibes connected to a large catchment with a relatively low curve number (CN(II) = 82) will not completely fill during 8 out of 23 years.

An important parameter for runoff collection is the rainfall depth at which runoff starts. According to Eqn (2), runoff is generated only when the daily rainfall exceeds a threshold of $0{\cdot}2S$. This threshold depends on the curve number and varies between 1·57 mm for catchments consisting mainly of rock outcrops during wet conditions (CN(III) = 97) to 25 mm for vegetated slopes with thin soils during dry conditions (CN(I) = 67). The wide range between these thresholds once again demonstrates the spatial variability in runoff on semi-arid slopes. The thresholds calculated above are in agreement with measurements of the minimum rainfall depth that produces runoff in other (semi)-arid landscapes: 5 mm on rocky slopes in the Negev, Israel (Lavee *et al.*, 1997), 5 mm of high intensity rainfall or 15 mm of low intensity rainfall on coarse stony slopes in New South Wales, Australia (Brown & Dunkerley, 1996), 4·5 mm h^{-1} on bare bedrock to 7·5 mm h^{-1} on rocky slopes in the Negev, Israel (Yair, 1992) and 10 mm on slopes with thin soils on mica-schist in Rambla Honda, south-east Spain (Nicolau *et al.*, 1996; Fig. 1).

Viability of the aljibe system

The current demand for water is difficult to assess, since the herds migrate, vary in size depending on the availability of grazing land and have a number of water sources at their disposition. Therefore, estimates will be based on water consumption of similar sized aljibes in Tunisia (Claude & Bourges, in press) and historic data on the size of flocks and number of aljibes in Almeria province (Cara Barrionuevo, 1996). A low water consumption between 0·5 and 1·0 m^3 day^{-1} can be assumed for small aljibes serving individual farms or for the large aljibes in the Sierra de Gata during summer. The latter value corresponds approximately to the water consumption of six families (40 persons and 70 sheep or goat) registered for a cistern of 160 m^3 in Tunisia (Claude & Bourges, in press). However, the most important function of the aljibes in the study area is to provide water for the livestock hibernating in the coastal plains and low Sierras. In fact, 80% of all remains of aljibes in Almeria province were found in this winter grazing area (Cara Barrionuevo, 1996). From local archives (1725–1775 AD) Cara Barrionuevo (1996) calculated the average water consumption per aljibe to be 4·2 m^3 day^{-1} based on the assumption that 60% of the sheep and goats and 45% of the cows and horses hibernate in the pastures around Tabernas, Nijar and Dalias (Table 2).

Let us consider the water balance of one of the most vulnerable aljibes in the driest part of the study area: a relatively large volume (153 m^3) connected to a catchment (5·81 ha) with a low runoff curve number (CN(II) = 83). The number of days during which this aljibe contains water has been estimated based on the daily rainfall records using the runoff curve method (Fig. 6(a)). The median annual rainfall for the last 25 years (225 mm) allows this aljibe to sustain a water consumption of 4·2 m^3 day^{-1} for 40 days and a water consumption of 1 m^3 day^{-1} for 160 days. It is evident from Fig. 6(a) that at present the catchments in the Sierra de Gata with low runoff curve numbers can not sustain the historic water consumption of the migrating flocks even for part of the year (7 months). In contrast, a small aljibe in the Sierra the Gador provides a secure water supply to support at least one family and their livestock (0·5 m^3 day^{-1}) for a whole year (Fig. 6(b)). In order to explain this discrepancy we need to look closer at the trends in annual rainfall and design of the water harvesting systems. The rainfall data

Table 2. *Historic water consumption in the study area based on archives for the period 1725–1775 after Cara Barrionuevo (1996)*

	Sources of water					Number of livestock	
	aljibes	ponds	wells	springs	total	sheep & goats	cows & horses
Tabernas	4	1	0	3	8	13,333	1467
Nijar	6	5	2	0	13	21,667	2383
Dalias	6	2	1	0	9	15,000	1650
Total Almeria	16	8	3	3	30	50,000	5500
						water consumption★ 4·2 m^3 day^{-1} $aljibe^{-1}$	

★ Water consumption: sheep and goats, 1 l day^{-1}; horses and cows, 38·5 l day^{-1}; 60% of sheep and goats and 45% of cows and horses graze in the winter months.

we used to assess the water availability in the aljibes contained a series of dry years (1975 onwards) and therefore the historic water demand is probably unrealistic for this dry period. According to Palutikof *et al.* (1996) the annual rainfall decreases from the 1950s onwards, and in particular the 1970s and 1980s were much drier than average

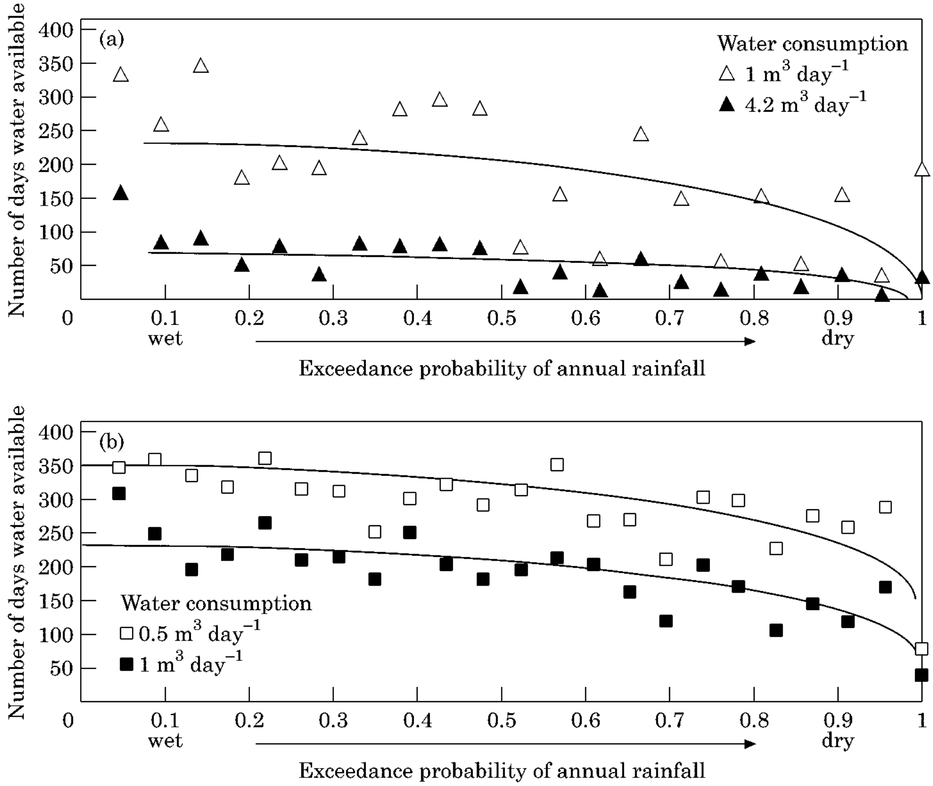

Figure 6. Annual water availability in two aljibes with different catchment characteristics and annual rainfall (247 mm in Sierra de Gata and 422 mm in Sierra de Gador): (a) aljibe (153 m^3) in Sierra de Gata connected to a catchment of 5·81 ha with a CN(II) = 83; (b) aljibe (52 m^3) in Sierra de Gador connected to a catchment of 0·29 ha with a CN(II) = 95.

(Fig. 5(a)). However, the design of the water harvesting system is probably even more important than trends in annual rainfall, since similar systems still function in much drier environments such as Tunisia (169 mm year^{-1}; Claude & Bourges, in press) and India (100–450 mm year^{-1}; Samra *et al.*, 1996).

The runoff curve number of the catchments of the large aljibes is rather low (Fig. 4). It can be observed in the field that in the past the catchments used to be treated in order to increase runoff production: vegetative cover was kept to a minimum, soils were trampled to increase crust formation and reduce infiltration, conduits were better maintained and occasionally the thin soil was removed to expose the bedrock. Another factor that can improve the viability of this water harvesting system is the relation between the volume of the aljibe and the catchment area (V/S in m^3 ha^{-1}). The non-linear relation between V and S already indicates that the V/S of the large aljibes is relatively low (Figs 3 and 4). The effect of aljibe volume on the availability of water was tested for the example shown in Fig. 6(a) using a daily water consumption of 1 m^3 (Fig. 7). During wet and average years ($p = 0{\cdot}1$ and $p = 0{\cdot}57$) the access to water reaches an optimum for a V/S of approximately 60 m^3 ha^{-1}. This value is comparable to the optimal V/S found for the Tunisian cisterns (Claude & Bourges, in press). Many of the new aljibes, which drain dirt roads, and the aljibes on the gently sloping plains in fact have high V/S ratios.

The efficiency of the water harvesting systems presented in this study is determined mainly by the runoff curve number of the catchments on hillslopes, artificial surface sealing of catchments on gently sloping plains and the design of the system to obtain a volume to catchment ratio of 60 m^3 ha^{-1}. These indigenous systems will play an important role in the sustainable development of semi-arid and arid regions, where the demand for water is ever increasing due to threats of desertification and an increasing population density (Le Houérou, 1996).

Conclusion

Collection and storage of runoff from hillslopes in underground cisterns (aljibes) is an old and well established technique in the semi-arid part of Spain. The water in these aljibes is mainly used by herds of sheep and goats, although other uses were observed (domestic, forestry, mines). These aljibes are constructed to collect runoff from nearly impermeable areas (rocky slopes, dirt roads, gentle slopes with a crusted surface and even complete headwater areas). The non-linear relation between catchment area and

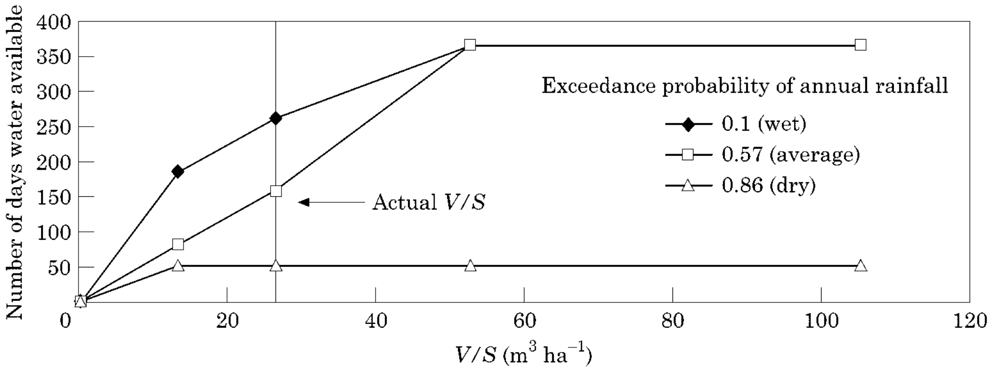

Figure 7. Effect of volume to surface ratio (V/S) on water availability of the water harvesting system examined in Fig. 6(a).

aljibe volume demonstrates that they were designed to collect a maximum of runoff and that the runoff coefficient decreases with catchment area. In particular, the geomorphic position of the aljibes (downslope of steep slopes with rock outcrops and avoiding the colluvial mantle) is in agreement with the discontinuous character of runoff in (semi-) arid landscapes. The large temporal variability of rainfall determines the viability of the water harvesting system. In areas with around 250 mm annual rainfall, the catchments with runoff curve numbers below 90 fail to produce enough runoff to fill the aljibes during periods of drought. This study shows that the aljibe water harvesting system is still viable provided that the runoff coefficient of the catchments is high and the size of the aljibe is adapted to the size of the catchment so that water loss by overflow is minimal (V/S ratio > 60 m^3 ha^{-1}). Removal of vegetation, trampling and formation of a surface crust and maintenance of runoff conduits will all contribute to increase the runoff generation from the catchments. Indigenous techniques such as the aljibe system could provide an additional source of water to alleviate the ever increasing demand in semi-arid and arid regions.

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