

## Estimating groundwater recharge induced by engineering systems in a semiarid area (southeastern Spain)

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**Abstract** The scarcity of water resources in semiarid regions is usually accompanied by brief periods of quite intense precipitation that can generate potentially catastrophic floods. In such regions, the use of runoff water for aquifer recharge can contribute to both flooding prevention and effective management of water resources. This paper presents the results of a study undertaken in southeastern Spain focusing on the recharge induced by a number of engineering structures (check dams) and gravel pits. The current network of check dams consists of 107 dams, of which 64 are located over permeable substrates and so we can induce recharge of the storm runoff retained therein. The hydrological model was performed using the curve number method (CN) of the Service for the Conservation of Soils, utilizing code HEC-HMS. Results indicate that the proportion of runoff infiltrated through the check dams varies from 3% to more than 50%, according to the effective volume of water dammed and the substrate. In addition, hydrological modelling was carried out in a subbasin taking advantage of the presence of one of a number of gravel pits. The gravel pits are situated in the apical sectors of alluvial fans that overlie hydrogeological units that are widely overexploited, and so they are

well positioned for use for artificial recharge. In this case, we conclude that a pit is capable of retaining and infiltrating the combined runoff volumes for various return periods (5, 25, 50, and 100 years). Furthermore, the simulation carried out suggests that the recharge processes in these environments are intimately linked to episodic storm events. The incorporation of hydrogeological criteria in the design and construction of check dams could therefore be very useful for the optimum management of water resources in semiarid zones.

**Keywords** Check dam · Groundwater · Incidental recharge · Gravel pit · Hydrological modelling · Semiarid areas · Storm runoff

### Introduction

The fundamental hydrological characteristic of semiarid regions is the pronounced spatial–temporal variability in their water resources. The water cycle in these environments is typified by high evapotranspiration rates and low precipitation, which in turn produces a deficit in runoff and in groundwater recharge. In semiarid Mediterranean mountain regions, this lack of precipitation, together with the low vegetation cover and steep slopes, favours erosion and catastrophic floods. Moreover, the rapid growth of agriculture and ever-growing population pressure means that the management and use of water resources in such zones are particularly problematic.

This situation is especially challenging in southeastern Spain, where most of the water resources are supplied from groundwater. This has led to the

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overexploitation of numerous aquifers and, as a consequence, to a serious limitation on economical development. Recently, there has been an increase in research on the relationship between surface water and groundwater resources, especially with regard to transfer mechanisms and integrated catchments management. In addition, considerable effort has been made by various levels of government to locate and develop new and alternative water resources, such as desalination, wastewater reutilization, or artificial recharge of aquifers. In particular, artificial recharge by means of basins, rills, ditches or other structures is being increasingly tried in water resource management projects since it confers numerous advantages.

Bouwer (2002) presented a detailed review of the current state of knowledge for artificial recharge, describing the possible techniques to achieve it, as well as the various determining factors in the process. Bouwer distinguished a number of concepts related to groundwater recharge: natural recharge, defined as the difference between water input into the soil and output; enhanced recharge, defined as the increase in the amount of water that reaches the soil by means of appropriate management of the vegetation cover; induced recharge, achieved by bank infiltration systems using pumping wells close to a river; and incidental recharge, brought about by human activities not intended for recharge of groundwater, such as sewage disposal by septic tank or deep percolation from irrigated fields.

Artificial recharge requires the presence of permeable geological strata with high transmissivity and storage capacity. The main disadvantage is the gradual silting up of the recharge structures, and for this reason careful design and suitable management are essential. The water used for the artificial recharge may come from surface runoff (continuous or discontinuous), wastewater that has received some degree of treatment (generally urban wastewater), and/or groundwater pumped from another aquifer. In semiarid areas, where rainfall is intermittent and sometimes very intense, the floodwaters can be recharged into aquifers using existing structures (such as check dams or gravel pits) without the need for heavy investment, although appropriate maintenance is required.

The principal aim of this study is to evaluate the hydrogeological efficiency or incidental recharge of a series of engineering structures (check dams and gravel pits) whose initial design did not contemplate aquifer recharge, and the establishment of a proposal for managing stormwater runoff in a mountainous, semiarid area of southeastern Spain.

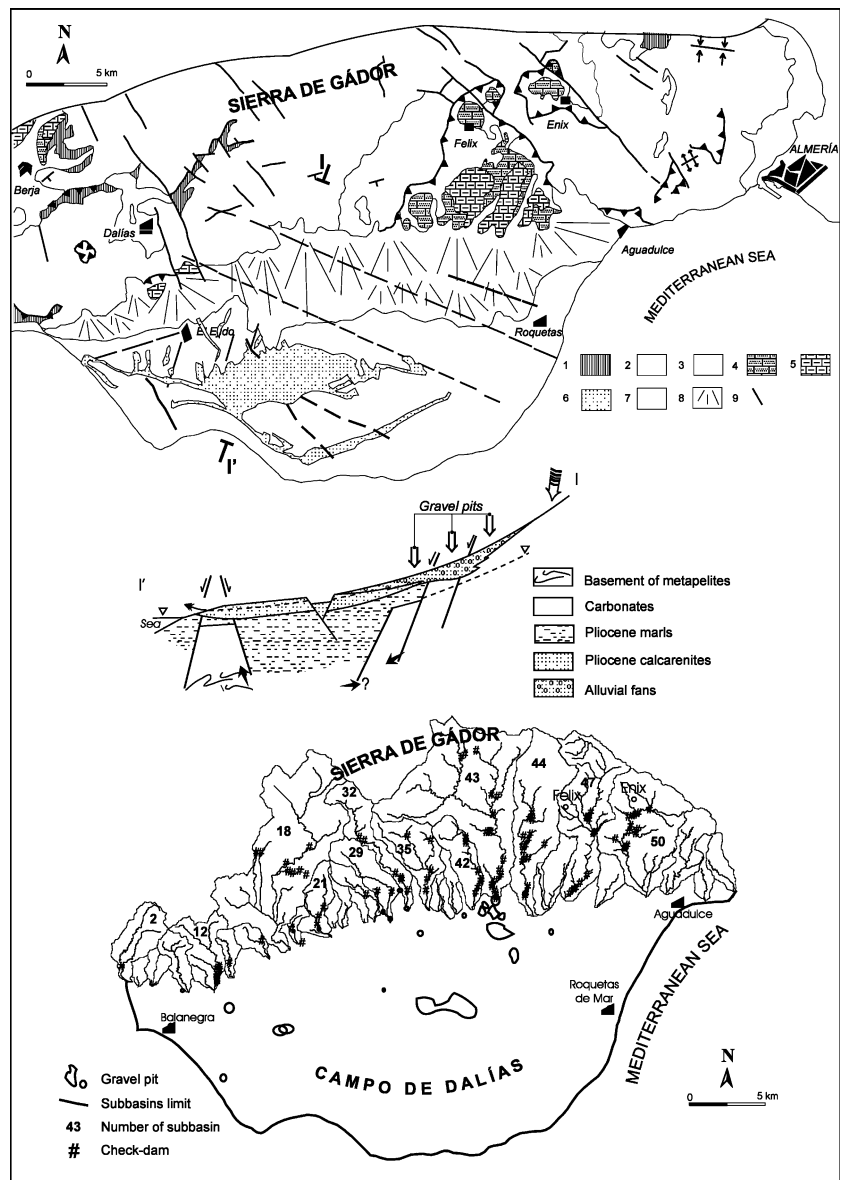
## Site description

The study was carried out on the southern face of the Sierra de Gádor and in the Campo de Dalías, within the province of Almería, which is situated in the extreme southeast of Spain (Fig. 1). The total area of the Campo de Dalías region is close to 320 km<sup>2</sup>, and the southern slopes of the Sierra de Gádor cover a similar area. The study area is made up of 55 small basins with surface areas of between 1 and 54 km<sup>2</sup> (Fig. 1). Morphologically, the catchments range from quite rounded (infrequent) to extremely elongated (common). The drainage network is predominantly dendritic, although in certain sectors it is broken up into a more angular pattern, likely due to the influence of the main fractures in the zone. Slopes are very steep, giving rise to deep, narrow channels, with more than 40% of the total area showing a gradient in excess of 35%. On the lower slopes, the principal characteristic of the channels is their high width/depth ratio. These ephemeral gravel streambeds (called *ramblas* in the Spanish Mediterranean region) are dry for most of the year, but become very active during flood events. Of these ramblas, only one (5) drains extreme-event discharges directly to the sea, while the rest carry their waters into the central part of Campo de Dalías which, due to tectonic reasons, is an endorheic basin.

The climate in this area is Mediterranean, characterized by warm, dry summers and mild winters. The semiaridity of the zone is conferred by a combination of scarce precipitation (240 mm in the Campo de Dalías and 400 mm on the southern slopes of Sierra de Gádor, with a clear topographic influence and declining from west to east), strong insolation (about 2,900 h year<sup>-1</sup>), interannual variability in rainfall (22–35%), and high potential evaporation (about 900 mm year<sup>-1</sup>). The intra-annual rainfall has two relative maxima in November and January and two minima in July and August. Temperature increases from a mean of 16°C in the mountains to 18.7°C in the Campo de Dalías, where January is the coldest month (10.2°C) and August is the hottest (27.2°C). Like the rest of the Mediterranean basin, this area is susceptible to very intense precipitation, with up to 200 mm falling within a 24-h period on occasion (Martín-Rosales et al. 1996).

The oldest outcrops are Permian and Triassic metapelites and carbonates, respectively, that cover almost the entire southern part of Sierra de Gádor. These carbonate deposits can reach a thickness of over 1,000 m, although there may be intercalations of calcoschists and marly limestone. Above these materials

**Fig. 1** Study area including a geological scheme together with a cross-section, and a scheme with numbered subbasins and location of the principal gravel pits and check dams. 1 Gadore metapelites, 2 Gador carbonates, 3 Felix metapelites, 4 Felix carbonates, 5 Miocene calcarenites, 6 Pliocene calcarenites, 7 Quaternary sediments, 8 Quaternary alluvial fans, 9 Faults



are Miocene deposits, made up of calcarenites in the outcrops and marls and gypsum beneath a Plio-Quaternary infill. The Pliocene strata are quite thick throughout the Campo de Dalías; their base comprises up to 700 m of blue marls, which contain increasing numbers of sandstone intercalations towards the top of the series (Fig. 1). Quaternary materials are present along the entire southern flank of the Sierra de Gador, comprising large alluvial fans that occasionally exceed 150 m in thickness. These alluvial fans are typical of arid and semiarid mountainous areas and comprise particles of all sizes, from boulders and blocks to silt and clay, with highly variable sorting. In addition, there are muddy and marly deposits related to the salt lakes,

and old and recent beaches along the present-day coastline.

The Campo de Dalías is tectonically very complex (Fig. 1) and this, in turn, confers great complexity to the geometry of the hydrogeological units (Pulido-Bosch et al. 1991; Vallejos et al. 1997; Molina et al. 2002). The aquifers of this area are grouped into three hydrogeological units: the Balanegra Unit (situated at the western end of the Campo), composed of Permian carbonates and Miocene calcarenites; the Balerma-Las Marinas Unit, comprising Pliocene calcarenites whose impermeable bottom corresponds to the Miocene marls; and the Aguadulce Unit (the easternmost of the three), consisting of Permian

limestone-dolomitic deposits, and Miocene and Pliocene calcarenites (Pulido-Bosch et al. 1991, 1993; ITGE 1995; Molina 1998). The upper detritic aquifer is scarcely exploited due to high salinity, so the piezometric levels are rising due to recharge by irrigation water and wastewater infiltration. Exploitation therefore centres on the underlying limestone and dolomite deposits, where the piezometric levels are several hundred metres below the ground surface, and even below sea level in certain parts—giving rise to marine intrusion (Pulido-Bosch et al. 1991).

At present some 20,000 ha are covered by highly profitable early-season greenhouse crops in the Campo de Dalías region. Their importance is such that these crops comprise the driving economic force in Almería province. It has been estimated that the economic activity related to out-of-season agriculture is worth over two billion dollars. This agricultural impetus, however, has been achieved only after a great deal of work by growers and by the government and at high environmental cost. The greenhouses are dependent on the groundwater that derives mainly from infiltration within the Sierra de Gádor terrain. González-Asensio et al. (2003) estimated the annual water use at 140 Mm<sup>3</sup> for 1999/2000 in the Campo de Dalías, while the available water resources are estimated to be some 100 Mm<sup>3</sup> year<sup>-1</sup>. The imbalance between the renewable resources and the intense exploitation of the carbonate aquifers along the edge of the sierra is generating situations such as the lowering of the water table, a drop in water quality, marine intrusion, and the mobilization of brines (Pulido-Bosch et al. 1998).

## Engineering structures and human activities

### Check dams

The Sierra de Gádor has undergone intense deforestation, which has led to severe degradation of vegetation cover. The cause of this tremendous loss of vegetation is found in the historical use of wood for boat construction, mining in the area during the nineteenth and twentieth centuries, and intense oak and pine tree felling for fuel. Almería is now one of the most deforested provinces in Spain, in contrast to the significant forests it had as recently as the eighteenth century. Today, vegetation in the catchments consists of degraded matorral and steppe. Much of the area is covered by dry land tillage, almost completely abandoned now.

Along the southern mountain slopes of the Sierra de Gádor, there are 107 small retention and flood-control dams (check dams), originally designed with the aim of reducing, counteracting, or preventing the transport of solids along the stream bed. This type of structure is common in reforestation projects in mountain areas, where high-gradient mountain streams are often prone to channel incision. They are all gravity-fed structures, trapezoidal in cross-section, and provided with weep holes at different levels to avoid prolonged loading during floods. The inventory lists six solid-concrete dams, 29 gabions, and 72 masonry dams. Fifty-nine percent of the structures are situated in only four of the basins, namely the ramblas of Carcáuz, Cañuelo, Vícar, and Las Hortichuelas (Table 1).

**Table 1** General characteristics of the subbasins, distribution of check dams and results of the simulation

No.	Stream	Drainage area (km <sup>2</sup> )	Curve number (CN)	Storm depth (mm)	Runoff volume 10 <sup>6</sup> m <sup>3</sup>	No. of check dams	Effective volume (m <sup>3</sup> )	Induced recharge <sup>a</sup> (%)
2	La Estanquera	9.0	–	–	–	2	0	0
12	Los Infantes	10.5	–	–	–	7	0	0
13	Balanegra	2.3	69.3	64	0.02	1	531	7.0
17	Hornales	2.1	68.9	68	0.02	1	940	13.5
18	Almodete	23.2	67.2	76	0.25	9	14,600	13.5
20	Real	1.4	–	–	–	2	0	0
21	Ancho	5.0	70.2	72	0.06	2	1,460	6.2
28	El Capitán	2.7	68.5	75	0.03	1	308	3.2
29	Andrés Pérez	7.1	67.8	77	0.08	1	5,042	11.7
32	El Aguila	10.8	68.9	81	0.15	6	34,186	52.5
35	La Maleza	12.4	70.1	80	0.20	5	11,860	7.0
42	El Tartell	6.6	74.2	78	0.13	7	8,745	7.3
43	Carcáuz	51.5	71.3	85	0.85	20	47,090	7.3
44	El Cañuelo	23.3	77.6	83	0.58	17	41,880	8.1
47	Vícar	13.4	75.6	79	0.23	13	12,095	5.7
50	Las Hortichuelas	19.6	79.8	65	0.39	13	25,116	6.5
Total					2.99	107	203,853	

<sup>a</sup> Induced recharge expressed as percentage of runoff volume

The original reservoir volume of the entire network of check dams was  $262,000 \text{ m}^3$ , but this has since been reduced by  $42,000 \text{ m}^3$ . The loss in capacity has been greater in the eastern basins, reflecting the larger surface area of impermeable and easily eroded outcrops (calcoschists and phyllites), as well as the greater deforestation and human impact that these areas have suffered. The calculated sediment yield is  $50 \text{ m}^3 \text{ km}^{-2} \text{ year}^{-1}$ , although in some basins values of nearly  $2,100 \text{ m}^3 \text{ km}^{-2} \text{ year}^{-1}$  have been estimated (Martín-Rosales et al. 2003).

### Gravel pits

The cultivation system in the Campo de Dalías area is highly unusual in that it does not require favourable edaphic conditions: greenhouse construction consists of laying a silt-clay bed followed by a layer of animal manure or compost, which is then covered by a layer of gravel. Most of the lutitic materials are derived from a series of pits excavated in the distal parts of the alluvial fans. It is estimated that these quarries cover a surface area of 1,150 ha. The volume of material extracted (basically lutites) is on the order of  $8 \times 10^6 \text{ m}^3$ , which gives some idea of their importance. The gravels were formerly taken from the beach areas, but the prohibition of extractive activities by the authorities dictated that new extraction points be found, and these extraction areas are now mainly located in the apical parts of the alluvial fans. Proliferation of these kinds of activities has created a serious environmental impact, although in some areas the abandonment of boreholes has resulted in the appearance of wetland habitats of notable ecological interest (Pulido-Bosch et al. 2000).

Normally gravel pits are located at the outlets of the larger ramblas (Carcáuz, Bernal, La Maleza, and Andrés Pérez), where the riverbeds are wide enough to serve as impromptu roadways. The exploitation is open-pit and the walls are stepped in order to prevent rock-falls and slides (Fig. 2). No clear criterion exists for the extractions, as they may be abandoned for long periods then suddenly be activated again.

### Materials and methods

The initial topographic information was a DEM (digital elevation model) with a resolution of 10 m. Other GIS data sets used in this analysis were derived from a variety of sources including: (1) bedrock geology (1:50,000 scale), (2) vegetation type and land use, and (3) location of check dams and gravel pits and other



**Fig. 2** A 13-m high masonry check dam in subbasin 32 (Águila subbasin), and view of one of the gravel pits in Carcáuz rambla

field surveys. The stages of this analysis entailed correction of the DEM, calculation of the direction of flow, definition of the drainage network, delimitation of the subbasins and their vectorization, as well as revision and modification of the results. All these tasks were implemented using Geo-HMS software (USACE 2000), running as an extension of a Geographic Information System program.

### Field survey procedures

An inventory was made of all existing check dams throughout the sierra, making detailed records of their dimensions, reservoir capacity, and retained sediment volume. In addition, detailed mapping was carried out of the geological deposits cropping out in each of the reservoir basins.

The infiltration capacity of the beds of the water-courses was estimated from the results of twenty double-ring infiltrometer tests. Four further infiltration tests were done in the gravel pit selected for this study, using the Haefeli method (González de Vallejo

et al. 2002); the test was performed in a ditch excavated in the shape of an inverted pyramidal trunk with a square base. The hydraulic conductivity ( $\text{m s}^{-1}$ ) was calculated according to the following expression:

$$k = \frac{Q/b^2}{(27h/b + 3)}, \quad (1)$$

where  $Q$  is the flow used to maintain a certain height of water column ( $\text{m}^3 \text{s}^{-1}$ ),  $b$  is the width of the base, and  $h$  the height of the water column, both measured in metres. Lastly, the infiltration flow  $Q_{\text{inf}}$  ( $\text{m}^3 \text{s}^{-1}$ ) is calculated by

$$Q_{\text{inf}} = k \cdot A, \quad (2)$$

where  $A$  is the wetted area ( $\text{m}^2$ ).

The hydraulic conductivity calculated according to the Haefeli method in the Carcáuz gravel pit was  $17 \text{ m day}^{-1}$ . The arithmetic mean hydraulic conductivity of the bed of the ramblas was  $3.96 \text{ m day}^{-1}$ .

### Hydrologic and hydraulic modelling

There are no records available in the stream-gauging stations nor measurements for basins with similar characteristics. The runoff modelling was done using the HEC-HMS code (USACE 2000). The option used in the present application to represent the rainfall-runoff processes is the curve number method (Soil Conservation Service 1972). With this method the runoff can be related to soil cover complexes and rainfall through a parameter known as a curve number (CN). Rainfall excess,  $Q$ , in the SCS method is related to the precipitation  $P$ , in millimetres, and the retention capacity of the basin  $S$ , also in millimetres, as given by Eq. 3.

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \quad (3)$$

The direct runoff computation was done using the unit hydrograph triangular method and the flow routing with the Muskingum-Cunge method (Cunge 1969). The transmission losses along the channels and the lamination effect of the dams were taken into consideration. For details of these methods see USACE (2000).

The CN is a function of the antecedent moisture condition (AMC), the lithology, and land use. The AMC is a function of the total rainfall in the 5-day period preceding a storm. It is considered an intermediate level

(AMC II) for soil saturation conditions. The fissured and karstified limestones were assigned to Group B of the SCS classification because of their elevated hydraulic conductivity. Over such lithology, the drainage network has a very low density, indicating a predominance of infiltration and elevated hydraulic conductivity. Moreover, on the surface, numerous exokarstic landforms can be seen, such as dolines, uvals, and caves, which indicate the prevalence of infiltration processes.

The phyllites are highly impermeable rocks in which the density drainage network is the highest. These materials were assigned to group D of the SCS classification. The calcoschists have intermediate hydraulic conductivity and are therefore assigned to group C. The alluvial fills in the watercourses have very high infiltration capacity but are not very abundant compared to the outcrops of other materials and were considered to belong to group A. The vegetation cover consists of trees planted as part of reforestation schemes at higher altitudes, although most of the catchment is occupied by shrub and nonirrigated crops. These features resulted in an assigned CN between 67 and 80 along the southern face of Sierra de Gádor (Table 1).

As part of our study, we examined extreme rainfall events. A frequency analysis was done using the daily precipitation series for 18 rainfall stations maintained by the National Institute of Meteorology, complemented by data from a thermopluviometric station belonging to the Water Resources and Environmental Geology Research Group (University of Almería). This station is fitted with a data-logger that covers a period of only 15 years. Annual maximum precipitation values were fitted to the Gumbel distribution (Gumbel 1958). This distribution has been extensively used in various fields including hydrology for modelling extreme events. It is a particular case of the three-parameter generalized extreme value (GEV) distribution. The Gumbel is usually preferred to the GEV because of its ease of calculation. Its probability density function is as follows:

$$f(x) = \frac{1}{\alpha} \exp \left\{ - \left[ \frac{(x - \beta)}{\alpha} \right] \right\}^{-\exp \{ -[(x - \beta)/\alpha] \}} \quad (4)$$

and its cumulative distribution function is expressed by

$$F(x) = e^{-e^{-(x - \beta)/\alpha}}, \quad (5)$$

where  $x$  is the value of the variable, and  $\alpha$  and  $\beta$  are the distribution parameters. They were estimated by the L-moments method (Hosking 1990):

$$\alpha = \frac{\lambda_2}{\ln 2} \tag{6}$$

$$\beta = \lambda_1 - 0.5772 \alpha, \tag{7}$$

where  $\lambda_1$  and  $\lambda_2$  are the first and second L-moments, defined as linear combinations of the probability-weighted moments defined by Greenwood et al. (1979). For the calculation of the parameters using the L-moments method, we refer you to Hosking (1990) and Stedinger et al. (1993). Validation of the Gumbel distribution model was achieved by means of the probability plot correlation test developed by Filliben (1975) and applied to the Gumbel distribution by Vogel (1986).

We have considered a design storm of 6 h of duration, which represents some 92% of the maximum precipitation in 24 h for this area (Heras 1976). The temporal distribution of the precipitation was determined by the triangular hyetograph (Chow et al. 1988), considering a storm-advancement coefficient of 0.083; that is, with the maximum intensity occurring 30 min after the onset of the storm.

#### Estimating induced recharge

To quantify the recharge induced by the dams, we considered only those dams located over permeable lithologies—limestones, dolomites, or calcoschists. Infiltration is virtually nonexistent from dams located over the impermeable phyllites. The gabions were also excluded from the analysis, since they are excessively permeable and so do not appreciably increase infiltration. Only 64 of the 107 dams promote infiltration of the water retained behind them. In addition, we defined the concept of effective reservoir volume as the combined volume of all the dams made of concrete or masonry constructed over permeable strata in a given basin. This concept provides a parameter that is indicative of the potential recharge of the basin.

On the basis of the above considerations, we calculated theoretical flood hydrographs for each of the 64 dams analysed for a 5-year return period. The infiltration rate generated in the reservoir behind each dam was computed in stages, as detailed in previous papers (Martín-Rosales 2002; Pulido-Bosch et al. 2002). Basically, it takes into account the height-volume curve of each dam, the hydrodynamic analysis of the dam by means of flow nets, the height-infiltration ratio, and the infiltrated volume for a given inflow hydrograph. The hydraulic conductivity used for the infiltration estimates in the check dam reservoirs was 5.20 m day<sup>-1</sup> for limestone and 0.43 m day<sup>-1</sup> for the

calcoschists, as deduced from pumping tests (Martín-Rosales 2002).

In one of the subbasins studied (rambla de Carcáuz, subbasin 43), the recharge induced by the gravel pits was considered. This is one of the most representative pits, having a surface area of 82,000 m<sup>2</sup>, a volume of 1.6 × 10<sup>6</sup> m<sup>3</sup> and a mean depth of 20 m (Fig. 3). In the simulation of induced infiltration various return periods were considered, resulting in different runoff hydrograph inflows to the gravel pit. In addition, height-volume curve and height-infiltration ratio were calculated beforehand. As mentioned above, the detritic alluvial deposit of the gravel pit has a hydraulic conductivity of 17 m day<sup>-1</sup>, determined using the Haefeli method.

In order to calculate the recharge induced by the gravel pit, the check dams situated on the catchment slopes had to be considered, both in terms of their detention effects as well as the recharge they induced. In this case the design hyetograph was constructed on the basis of the IDF curves deduced from the precipitation records at the thermopluviometric station installed in the middle of the catchment, which yielded 15 complete years of records. Figure 4 summarizes the procedure to calculate the infiltration in Carcáuz basin through check dams and in one gravel pit located at its outlet.

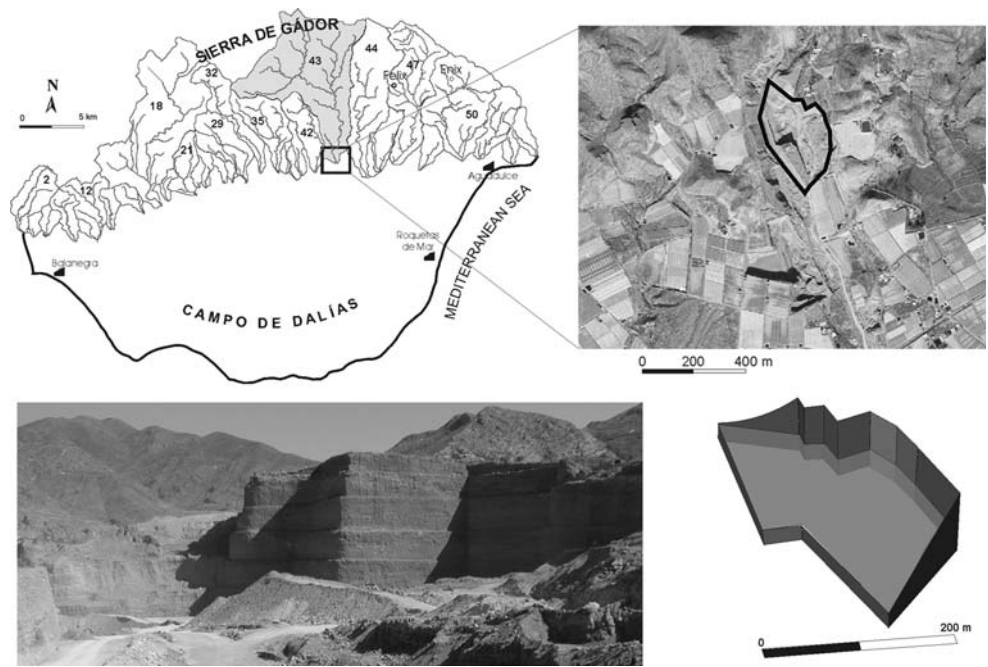
### Results and discussion

Maximum precipitation tends to be higher in the eastern part of the study area, which is more semiarid (Martín-Rosales et al. 1996). Here, a return period of 5 years gives values ranging from 37 to 86 mm day<sup>-1</sup>. The fit of the Gumbel distribution was satisfactory for all the stations employed. The values were consistent with those obtained using other methods, such as the partial duration series (Pulido-Bosch et al. 2002).

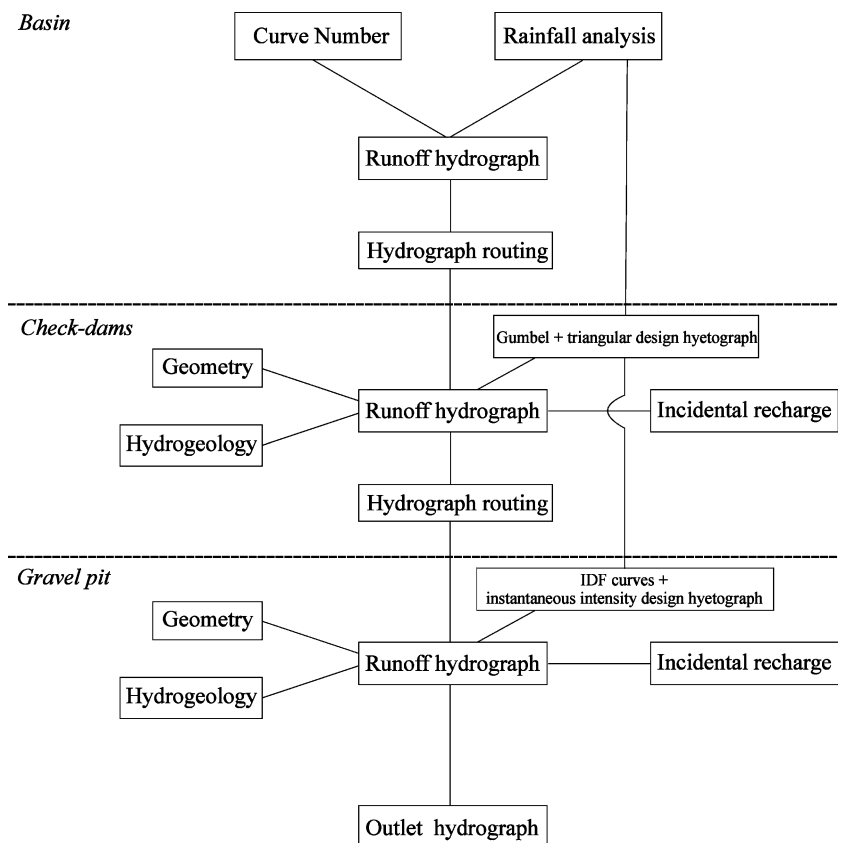
The effective reservoir volume obtained for the study area as a whole was 204,000 m<sup>3</sup> or 78% of the original reservoir volume (Table 1). The volume in the eastern part of the study area was greater due to the availability of more check dams. Four subbasins alone contributed 73% of the effective reservoir volume, namely Carcáuz (23%), Cañuelo (21%), Aguila (17%), and Hortichuelas (12%).

The maximum instantaneous flow ( $T = 5$  years) and the runoff volume were found to be greater in the more easterly subbasins, due to a predominance of impermeable rock deposits in this sector (phyllites and calcoschists), which results in a higher CN. Distribution of this runoff is highly uneven over the area as a whole.

**Fig. 3** Location of the gravel pit used for the simulation of induced groundwater recharge and a scheme showing the water depth inside the pit



**Fig. 4** Flowchart of the procedure followed to calculate groundwater recharge induced by check dams and a gravel pit in subbasin 43 (Carcáuz)



More than 60% of the runoff is generated in only three subbasins: numbers 43 (28.3%), 44 (19.4%), and 50 (12.9%). The most westerly and most permeable subbasins accounted for only a small percentage, indicat-

ing that runoff is collected only after extremely torrential rainfall.

Table 1 shows the proportion of runoff that infiltrates through the check dam network. This proportion



varies from 3% in the case of subbasin 28, which has only a single, small retention check dam, to more than 50% in the case of subbasin 32, which has six check dams and an effective reservoir volume in excess of 34,000 m<sup>3</sup>. However, the mean induced recharge is only 10%, since the check dams studied were not designed for this purpose, although appropriate planning would increase the possibilities for recharge in the area.

The relationship between the volume of water infiltrated and the volume of the reservoir is another parameter that is indicative of the hydrogeological efficiency of the engineering structures being studied (Fig. 5). In the case of the check dams overlying highly permeable strata (limestones and dolomites), the recharge induced is between two and four times the volume of the reservoir itself. Meanwhile, for the check dams overlying lower-hydraulic conductivity strata (calcoschists), the ratio is almost 1.

The hydrological modelling undertaken for gravel pit 1 in the Carcáuz subbasin (43) demonstrates, in a theoretical way, that this pit is capable of retaining and infiltrating the combined runoff volumes for various return periods (5, 25, 50, and 100 years), as shown in Fig. 6.

The time taken for water collected in the gravel pit to infiltrate is relatively short—less than one day in all cases, varying from 11 h for  $T = 5$  years to more than 20 h for  $T = 100$  years. According to the theoretical calculations examined, the stored volume never exceeds the capacity of the gravel pit reservoir: it varies from 10,000 m<sup>3</sup> for  $T = 5$  years, to more than 730,000 m<sup>3</sup> for  $T = 100$  years; that is, between 6 and 44% of the maximum useable volume, respectively. It should be pointed

out that the effect of silting caused by suspended sediment in the inflow was not considered even though this is one of the main problems that needs to be addressed in the practice of artificial recharge; nor did we consider the fact that the gravel pit would not perform in a homogeneous way during the recharge process.

It was not possible to validate these results since no gauging data were available. However, the hydrogeological efficiency of the gravel pits has been confirmed from field observations.

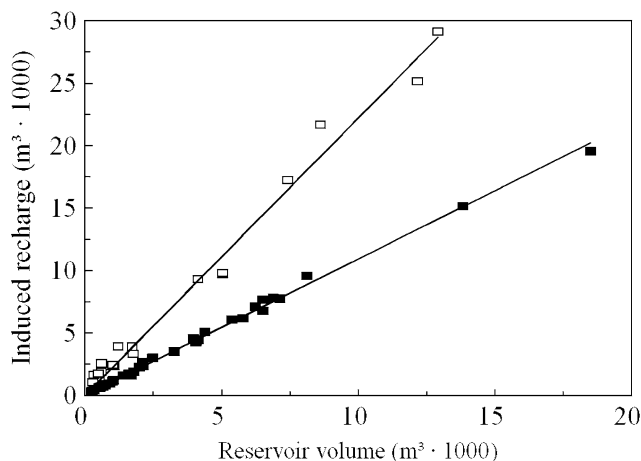
Consequently, on 7 March 1991, we took the opportunity to record a storm. During this storm, the elevated infiltration potential of the gravel pits in the Carcáuz rambla (basin 43 in Fig. 1) was confirmed. The storm lasted 20 h and 72 mm of rain fell, totalling 3.6 hm<sup>3</sup> over the basin as a whole. During the flash flood it was possible to gauge the flow directly, yielding a result of 3 m<sup>3</sup> s<sup>-1</sup>. The flash flood damaged some check dams through lateral erosion and subsidence of the central portion. These check dams are situated in the lower part of the basin. Several of the check dams overflowed, including some of the largest ones.

The most interesting observations occurred in the gravel extraction pits in the rambla de Carcáuz. These pits are located in the upper reach of the large alluvial fan of this rambla. During the flash flood it was clear that downstream of the gravel pit there was no runoff at all. This implies that practically all flow is infiltrated in this gravel pit, which therefore functions as a very effective recharge zone. In fact, the form and design of the extraction site further enhanced recharge of the aquifer. The pit had been excavated over the bed of the watercourse, which is blocked downstream, so that it functions like a dam. The appearance of the gravel pit a few days after the flood is indicated in Fig. 7. Note the layer of silt and clay lining the base of the pit, which suggests that the capacity for infiltration during subsequent floods would be significantly reduced.

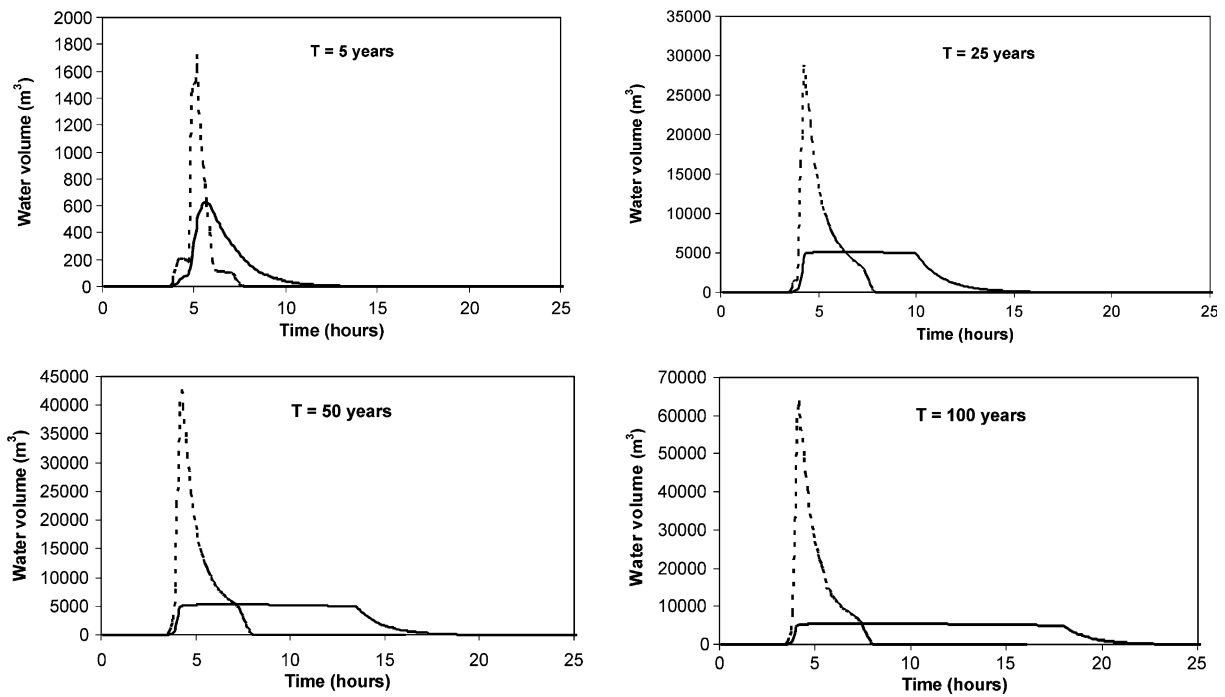
The high hydraulic conductivity of this part of the drainage network can be explained by the geology. These gravel pits have been dug in the apical part of the alluvial fans, where there is a predominance of coarser-grained materials. This morphology represents the recharge zone of the outwash fans (Simmers 1997).

**Conclusions**

The model applied demonstrates the high hydrogeological efficiency of certain engineering structures (above all, the gravel pits), whose design and initial purpose was not that of aquifer recharge. Although the check dam network led to an induced recharge of only

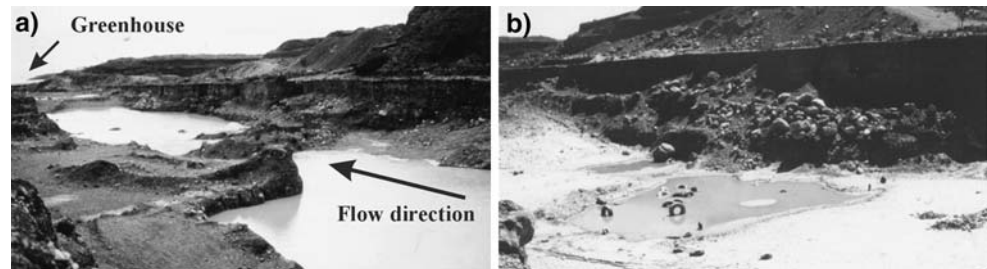


**Fig. 5** Reservoir volume versus induced recharge of check dams (white squares dams over limestone; black squares dams over calcoschist)



**Fig. 6** Hydrographs of water volume inflow to the gravel pit (*dotted curve*) and infiltration flow (*continuous curve*) for various return periods

**Fig. 7** Photos of gravel pit in the Carcáuz rambla during a storm (**a**) and a few days afterwards (**b**)



10% of the runoff generated by the storm, some sub-basins showed special promise for achieving this end. The incorporation of hydrogeological criteria in the design and construction of retention check dams in semiarid zones could be very useful for the optimum management of water resources. In addition, the simulation undertaken demonstrated that the recharge processes in this type of environment are intimately linked to infrequent storm events.

Bearing in mind the intensive exploitation by man and the flood risk in the study area, it seems appropriate to utilize some of the existing gravel pits on the alluvial fans to undertake artificial recharge, since this would simultaneously reduce the risk of catastrophic floods. This option is relatively environment-friendly: its impact is minimal and it could be a highly efficient, low-cost option. The fact that the model indicates that

one could achieve a total recharge of the runoff generated gives some idea of the potential of these structures for use as artificial recharge lagoons, as well as a means of flood protection. The methods suggested, which consist of hydrogeological modelling combined with spatial analysis, allow the recharge capacity of abandoned gravel pits to be evaluated. In the case of the gravel pit studied here, the results demonstrate the high efficiency from a hydrogeological point of view, which is due both to the considerable dimension of the gravel pit and to the high hydraulic conductivity of the terrain.

It should not be forgotten that another result—of equal significance—would be the reduced risk of destructive floods in the Campo de Dalías. The advantage of using existing gravel pits, once their useful exploitation is over, is the concomitant reduction in cost of engineering works, since only certain

elements are required to be installed to upgrade them as infiltration lagoons.

Fine-tuning of these systems would have to include continuous maintenance operations, since we are dealing with structures whose efficiency can deteriorate after each heavy rainfall event; the accumulation of silts which accompany the runoff water would also lead to silting up of the infiltration structures, and so it would be necessary to de-silt the lagoon beds. If the existence of other similar gravel pits along the length of the alluvial outwash fans of the Sierra de Gádor were taken into account, a network could be designed that could be used for artificial recharge, aimed towards the combined use of surface and groundwater resources.

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