



Thematic week: Water and Land

Thematic axis: Land Use Planning, Forest Cover and Afforestation

Title of the presentation: Techniques for increasing aquifer recharge in semiarid regions

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Abstract: Principal potential methods for recharging aquifers in semiarid regions are presented. Scarcity of water resources in semiarid regions is often accompanied by brief periods of highly intense precipitation that can generate potentially catastrophic floods. In such areas, runoff water can be harvested for aquifer recharge providing valuable contributions to flood prevention and the management of water resources. We present a study undertaken in the south-eastern Spain in which the recharge from several check dams is calculated, as well as that from various gravel pits excavated to provide gravel for use in greenhouses. The gravel pits are situated in the apical sectors of alluvial fans overlying hydrogeological units that are widely overexploited, so they are well-positioned for use for artificial recharge. The study demonstrates the high hydrogeological efficiency of such gravel pits for this purpose.

Keywords: check dam, aquifer recharge, gravel pit, hydrological modelling

1. Introduction

Approximately one third of the earth's crust corresponds to arid and semiarid regions. These are traditionally sparsely populated areas, due in large measure to the scarcity of water. Even when the lack of precipitation is compensated by the presence of plentiful river flow originating in distant regions that enjoy a wetter climate, these arid lands are vulnerable to salinization of soils and water resources because of the elevated rates of evaporation. Examples include the delta of the River Nile, and the Aral Sea. In the case of the Nile delta, there has been a great agricultural transformation linked to the Aswan Dam and the downstream reservoirs (Sherif, 2002). Meanwhile, the Aral Sea suffered one of the greatest ecological catastrophes of the

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twentieth century as a consequence of poor water resources planning of the rivers that flow into this inland sea.

Against this, the key to the sustainable development of some regions is to maintain the equilibrium between water supply and demand, which becomes particularly difficult in the driest years of water scarcity. The solution to the water shortage problems can take different approaches depending on the constitution of the subsoil. For example, the presence of a large aquifer formation holding substantial water reserves could enable economic development over a certain period, even in the knowledge that the exploitation is essentially water-mining (Lloyd, 2002).

The climatic characteristics – scarce precipitation, interannual dry periods, marked year-to-year variation, and torrential rainfall – are reflected in the hydrology of the region: in the drainage pattern, the drainage network and in the flow, amongst other aspects. This means to say that the river beds are frequently dry, while on occasions they carry a prodigious flow. These peak flows, since they are exceptional, can be particularly destructive, above all in areas that lack adequate land-use planning, where Man's activities have invaded the normally dry riverbeds.

Such drawbacks are partially compensated by the fact that there is an ancient "culture" of water scarcity in these regions which has normally led to a familiarity with methods of water-saving and the establishment of ingenious systems to take full advantage of the scarce water available. The climatic conditions that are so unfavourable in certain aspects may mean that these regions are highly attractive for agriculture and tourism, activities that bring concomitant increases in water demand that make a model of sustainable development unviable. Advances in air-conditioning systems have also boosted the appeal of these hot, dry regions. In this context the private sector provide the dynamics, investing profits in the exhaustive exploitation of the environment and of available resources. The outcome, from the point of view of groundwater water resources, is an intensive exploitation of the aquifers.

Droughts as well as floods are characteristic of semiarid regions, and both make the management of water resources difficult. Droughts encourage intensive abstractions and the indiscriminate sinking of new boreholes. In the driest years, infiltration into the aquifer can be practically nil. In wet years and/or during high-intensity rainfall events, infiltration can be very high, especially if certain measures are taken. In these regions the uncertainties in the data are evident, since the observation infrastructure – usually sparse – are only seasonally or intermittently used; for example, the section of gauging stations can vary considerably from one rainfall event to another (Pulido-Bosch, 2005); silting or erosion can occur or, quite simply, the sensors may develop problems as a result of their sporadic operation.

2. The problems

The problems refer to the availability of water, which is not always well understood or well evaluated. Two groups of problems can be considered: those relating to the quantity of water available and those relating to water quality. Of the quantity issues, the most important have to do with the *spatial and temporal variation of rainfall*. Surface waters are very scarce and are

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frequently the only water available is groundwater. There is a lower threshold below which infiltration, or aquifer recharge, is practically negligible. In contrast, above an upper threshold, most of the rainfall will reach the aquifer.

The first aspect to be taken into account is the presence or absence of aquifers, the infiltration capacity and the mechanisms that control this. *Intensity of precipitation* is a key parameter: when it exceeds the infiltration capacity, runoff can be substantial and can give rise to flood flows of great destructive force. Obviously, in the case of impermeable strata, the risk of flooding is always greater. For all these reasons, water availability in semiarid regions can be virtually nil during years of scarce precipitation, and very high in wet periods. In terms of aquifer recharge, there will be years when inflow is zero, and others when more than 50 % of the rainfall infiltrates to recharge the aquifer. For this reason, the water balances in semiarid regions need always to be based on periods that are sufficiently long to be representative and cover both these situations.

The other great problem linked to water quantity stems from the economic importance of agricultural produce from these regions. The increase in the area under cultivation creates a parallel rise in water demand that frequently entails intensive abstractions from the aquifers. Based on this, some planners have deduced that there is no merit in exploiting groundwaters since they always become exhausted.

The problems of water quality in semiarid regions are often relegated to second place, given the overwhelming problems relating to water quantity. The water user seems to accept with resignation that the water will be of poor quality, but will not readily accept being without water. In salinized sectors only crops that are more tolerant to salt are grown (particularly tomatoes). Other problems related to water quality arise from the potential point sources, just as in any other climatic domain. Wastewater discharges, solid waste disposal and, above all, fertilisers and pesticides, degrade water quality, restricting its use as a potable supply – though it has less influence on agricultural applications.

3. Possible solutions

The solutions can affect each of the elements of the hydrological cycle, and putting them into practice can be straightforward, or complex and costly. In other cases, their application on a large scale is obviously unviable, but there are cases of application that are very favourable on a very small scale. Semiarid regions, inasmuch as they carry a long tradition of living with scarce water supplies, have developed systems and mechanisms that try to harvest water in any of its states. Table 1 summarises the various methods of water harvesting and aquifer recharge.

Atmospheric mist collectors using stone pyramids or other schemes (Laureano, 1999) have been employed since the times of the pharaohs. Humidity in the atmosphere can generate hidden precipitation of more than 1000 mm/year (Strupczewski et al., 2002), though the main difficulty comes in avoiding its subsequent evaporation. The *artificial rainfall* of the 1950s to 1970s

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seemed to be a panacea for problems of water shortage in semiarid and even desert regions (Brahan, 1986). Experiments have been done all over the world as part of large, ambitious projects and these have led to the conclusion that this method was cheaper, and offered far more advantages than, say, the desalination of seawater (Agnew and Anderson, 1992). It is a method routinely applied in certain states of the USA.

The best use of *runoff* is an ancient solution that uses systems to enable maintenance agriculture. It is possible that Precolombian cultures knew this technique; certainly they were well developed in the semiarid regions of South America after the arrival of the Spanish (the Mexican “water boxes”, for example; Brading, 1978; Hebert et al., 1999). The most widespread example is that of the “aljibe”, which abound over south-eastern Spain, and which continue to guarantee water for livestock in many rural areas (van Wesemael et al., 1998). In urban areas, architects have also shown their concern for setting up systems that can mitigate the negative impact that urbanization and tarmacking of the rural environment has on the water cycle, especially in terms of reducing infiltration and increasing surface runoff. Some of the most common practices (Ferguson, 1994) are the rainwater cisterns on roofs, vegetated surfaces overlying porous land, permeable pavements, porous asphalt and porous concrete, as well as infiltration collectors integrated into the urban environment.

Surface runoff, particularly during spate periods, can be exploited via infiltration into the bed of the watercourse itself, or by encouraging infiltration in lateral basins and ditches after constructing a take-off sluice. Applications on the southern face of the Sierra Nevada which may have been initiated by the Romans, were active under the Arab occupation and continue today; these are the *careos*, which exploit meltwaters for artificial recharge and guarantee water supplies through the summer and into autumn (Pulido Bosch and Ben Sbih, 1997). The “sand reservoirs” that abound in parts of Africa (Kiviiy and Sharma, 2002) can be considered a special case; these use the infill behind the dam itself for the storage of surface runoff. These water collection systems are sufficient to maintain 1,402,000 ha of cultivated land in Pakistán, 165,000 ha in Morocco, 150,000 in Somalia, 110,000 in Algeria, 98,000 in the Yemen, and 30,000 in Tunisia (Prinz, 2000).

The Andalusian Water Agency currently finances, on an experimental basis, a project for the construction of an impermeable barrier over a cross-section of the bed of the river Almanzora, the aim of which is to accumulate water in the “vaso” (pond) upstream of the barrier. This barrier rests on the impermeable substrate and does not extend as far up as the ground surface (which would impede ponding back of the river). The system is complemented by collectors constructed within the pond.

Reservoirs in semiarid regions face particular problems due to high erosive power of runoff waters, and the tendency for relatively rapid siltation (The Isabel II reservoir provides an extreme example: it was never put into operation because of the siltation that occurred following heavy storms after the dam construction had been completed). The other problem comes from the variation in flow that obliges oversizing any engineering works in order to guarantee the “regulation” of extreme rainfall events. If this were not done, there would be years then they

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would be totally empty and others when there would be overspill. For this reason, regulation based on mean inflows would carry poor guarantees. Flow in the river Almanzora, for example, falls between zero and 255 hm³/year.

3. Case Study: the southern face of the Sierra de Gádor (Almeria)

Site description

Sierra de Gádor and Campo de Dalías are situated in the extreme south-east of Spain (figure 1). The total surface of the Campo de Dalías region is close to 320 km², and the southern slopes of the Sierra de Gádor cover a similar surface area, with 55 small basins with surface areas of between 1 and 54 km² (figure 1). Morphologically, the catchments range from quite rounded (infrequent) to extremely elongated (frequent). The drainage network is predominantly dendritic, although in certain sectors it has an angular pattern, which can be interpreted as being an adaptation to principal fractures. 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 particularly active during flood events. Of these ramblas, only one (n° 5) drains extreme-event discharges directly to the sea, while the rest carry their waters into the central part of Campo de Dalías which, for tectonic reasons, comprises an endorheic basin.

This area is characterized by a combination of the 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), interannual variability of precipitation (22–35%) and high potential evaporation. The intra-annual pluviometric distribution is characterized by two relative maxima in November and January, and by very scarce rainfall in July and August. Temperature increases from an average of 16 °C in the mountains to an average of 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). This area is susceptible to very intense precipitation, with up to 200 mm falling in 24 h on occasions (Martin-Rosales *et al.*, 1996).

The oldest outcropping rocks are Permian and Triassic metapellites and carbonate rocks. These carbonate deposits can reach a thickness of over 1,000 m. Overlying these materials are the Miocene deposits, made up of calcarenites in the outcropping sectors and marls and gypsum beneath a Plioquaternary infill. The Pliocene terrains, widely developed throughout the Campo de Dalías, comprise up to 700 m of blue marls, which contain increasing number of sandstone intercalations towards the top of the series (Fig. 1). Quaternary materials are present along the whole of the southern edge of Sierra de Gádor, making up large alluvial fans that occasionally exceed 150 m thickness. The remaining strata found in the Campo de Dalías area are mostly beach sediments, both ancient and contemporary, together with silty deposits in sectors distant from the large alluvial fans. At present some 20,000 hectares of land are dedicated to the cultivation of out-of-season crops under plastic in the Campo de Dalías region.

Check dams and gravel pits

The Sierra de Gádor has been subject to intense deforestation, which has led to severe degradation of the vegetation cover. The cause of this tremendous loss of vegetation is found in the historical use of wood for boat building, extensive mining in the area during the 19th and 20th centuries, and the felling of oak and pine trees for fuel. Along the southern mountain face of the Sierra de Gádor there are 107 small retention and flood-control dams (check dams), originally designed with the objective of reducing, counteracting or avoiding the transport of solids along the stream bed. They are all gravity-fed structures, trapezoid in cross-section, and provided with weepholes at different levels to avoid prolonged loading during floods. The inventory lists 6 solid-concrete dams, 29 gabions and 72 masonry dams (Table 2).

The original reservoir volume of the entire network of check dams was 262,000 m³, but this has been reduced by 42,000 m³. The loss of capacity has been greater in the eastern basins, reflecting the larger surface area of impermeable and easily eroded outcrops (calcoschists and phyllites). The calculated sediment yield is 50 m³·km²·year, although in some subbasins values of nearly 2,100 m³·km²·year have been estimated (Martín-Rosales *et al.*, 2003). Normally gravel pits are located in the outlet of the larger ramblas where streambeds are wide enough to serve as ways of communication. The exploitation is open-pit type and the slopes have a step-shape in order to avoid the rock-falls and sliding of the slopes.

Estimation of the recharge

The initial topographic information was a DEM with a resolution of 10 metres. Other GIS data sets used in this analysis were derived from a variety of sources and include: (1) bedrock geology (1:50,000 scale); (2) vegetation type and land use; (3) location of check dams and gravel pits and other field surveys. The stages of this analysis entailed correction of the DEM employed, 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 obtained. All these tasks were implemented using Geo-HMS software (USACE, 2000), running as an extension of a GIS program.

The infiltration capacity of the beds of the watercourses 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 (in González de Vallejo, 2002); the test was performed in a ditch excavated in the ground in the shape of an inverted pyramid with a square base. The permeability coefficient k (m·s⁻¹) was calculated according to the following expression:

$$k = \frac{Q/b^2}{(27h/b + 3)} \quad \text{where } Q \text{ is the flow used to maintain a certain height of column of water (m}^3\cdot\text{s}^{-1}\text{),}$$

b is the width of the base and h , the height of the water column, both measured in meters. Lastly, the infiltration flow Q_{inf} (m³·s⁻¹) is calculated by: $Q_{inf} = k \cdot A$ where A is the wetted area (m²). The hydraulic conductivity calculated according the Haefeli method in the Carcáuz gravel pit was 17 m·day⁻¹. The mean hydraulic conductivity of the bed of the ramblas was 4 m·day⁻¹.

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The lack of stream-gauging records in the area, as well as an absence of measurements for basins with characteristics similar to those studied, forced a theoretic modelling of runoff. The code used was the HEC-HMS (USACE, 2000). The option used in the present application to represent the rainfall-runoff processes is the Soil Conservation Service (SCS) Curve Number method for runoff volume computation. The underlying theory of the SCS-CN procedure is that 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 mm and the retention capacity of the basin, S , also in millimetres, as given by the following equation:

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

Others options used were the unit hydrograph triangular method for direct runoff computation and the Muskingum-Cunge method for flow routing; in addition, transmission losses along the channels and the lamination effect of the dams were taken into consideration. The curve number is a function of the antecedent moisture condition (AMC), the lithology and the land use. The AMC is a function of the total rainfall in the 5-day period preceding a storm. The model requires the study of extreme rainfall events. This frequency analysis was done using the daily precipitation series for 18 rainfall stations maintained by the Instituto Nacional de Meteorología (INM), 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. This distribution (Gumbel, 1958) 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.

We have considered a design storm of 6 hours duration, which represents some 92 % of the maximum precipitation in 24 hours for this area (Heras, 1976). The temporal distribution of the precipitation was determined by the Triangular Hyetograph Method (Chow et al., 1988), considering a storm-advancement coefficient of 0.083; i.e., with the maximum intensity occurring 30 minutes after the onset of the storm. 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.

Results and discussion

Maximum precipitation tends to be higher in the eastern part of the study area, where the semiarid nature is more pronounced. Here, a return period of 5 years gives values ranging from 37 to 86 mm·day⁻¹. The fit of the Gumbel distribution was satisfactory for all the stations employed. The effective reservoir volume obtained for the study area as a whole was 204,000 m³, i.e. 78% of the original reservoir volume (table 2).

The time taken for water collected in the gravel pit to infiltrate is relatively short: it is less than one day in all cases, varying from 11 hours for T = 5 years to more than 20 hours 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 m³ for T = 5 years, to more than 730,000

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m³ for T = 100 years – in other words, between 6% and 44% of the maximum useable volume. It should be pointed out that the effect of silting – caused by the 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 was the fact that the gravel pit would not behave in a homogeneous way during the recharge process.

In practice, the realisation of such recharge experiments in the basins poses certain problems, so that certain precautions need to be taken (Pulido-Bosch *et al.* 2005). The basins need to be equipped with baffle walls to dissipate the flow energy, and encourage settlement of fine particles. To facilitate inflow into the installations, a take-off weir could be built in the rambla itself, as well as a sluice into the basin, as necessary. Both structures would have to be furnished with floodgates/sluice gates to allow regulation both of the floodwater in the rambla and the flow into the infiltration basins. In turn, a gauging flume could be installed in the inlet so that the inflow could be monitored. The installation would be completed with a spillway downstream of the intake weir, fitted with a further gauging flume. Monitoring instrumentation could include the installation of piezometers in the vicinity of the infiltration basins to measure the effect of the volume infiltrated on the recharged aquifer, as well as the aquifer's response to different events.

One of the principal problems faced in the artificial recharge of aquifers using infiltration basins is that of *silting*, which may occur due to mechanical, biological or chemical processes. To avoid silting it is recommendable to install a gravel filter at the base. Nonetheless, after each recharge event, it would be advisable to clean silted elements when the silt penetration is not too deep. When there is deep silting, the layer of silt can be removed along with the upper part of the natural soil layer, and the sand or gravel filter in order to replace or wash them. In addition, a decantation system using stepped basins can be emplaced upstream of the recharge structure.

A further problem that can arise in recharge by means of infiltration basins is that of the instability of the taluses. To address this, one must start with a geotechnical study to understand the sequence that the works must follow, as well as the preventative or corrective measures to be taken in any particular case, and stabilise the slopes against the risk of landslide.

4. Conclusions

In semiarid regions it is possible to augment available water resources by constructing “soft” engineering works, which come at relatively low cost and have little environmental impact, whilst being able to reduce soil erosion and encourage laminar flow of destructive floodwaters. It does not appear that large volumes can be guaranteed with these systems, though with the support of other human actions on the environment, such as gravel pits, quarries and mining voids, the volume recharged can be quite considerable.

In terms of the southern face of Sierra de Gádor, the model applied demonstrates the high hydrogeological efficiency of certain engineering structures (above all, the gravel pits), whose design and initial purpose was distinct from that of aquifer recharge. Though the check dam

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network led to an induced recharge of only 10 % of the runoff generated by the storm, some subbasins were shown to be especially promising for achieving this purpose.

The methods suggested, consisting 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 permeability of the terrain.

Fine-tuning of these systems would have to include continuous maintenance operations, since we are dealing with structures whose efficacy can deteriorate after each heavy rainfall event; the accumulation of silt that accompanies the runoff water would also lead to silting up of the infiltration structures, and it would be necessary to de-silt the lagoon beds. If the presence of other, similar gravel pits extending over 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 at the combined use of surface and groundwater resources.

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Tables and Figures

- A) Rainfall and fog harvesting
 - Artificial rainfall
 - Fog harvesting

- B) Rain and run-off harvesting
 - a) *Rural environment*
 - “Cajas de agua” (lit. “water boxes”)
 - Storm water
 - Infiltration in stream bed
 - Check dams, pools and ditches
 - Careos*
 - Sand dams
 - Conventional dams
 - Collector tanks
 - Infiltration wells
 - b) *Urban environment*
 - Roof collection systems
 - Porous asphalts, porous concrete
 - Open-celled pavements with vegetation

Table 1.- Some methods of water harvesting and aquifer recharge

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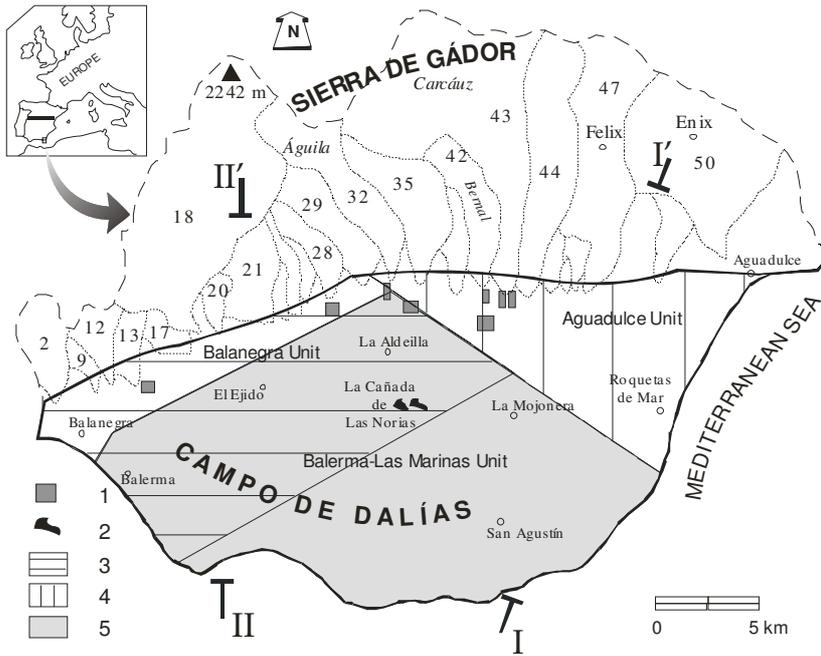


Figura 1 A.

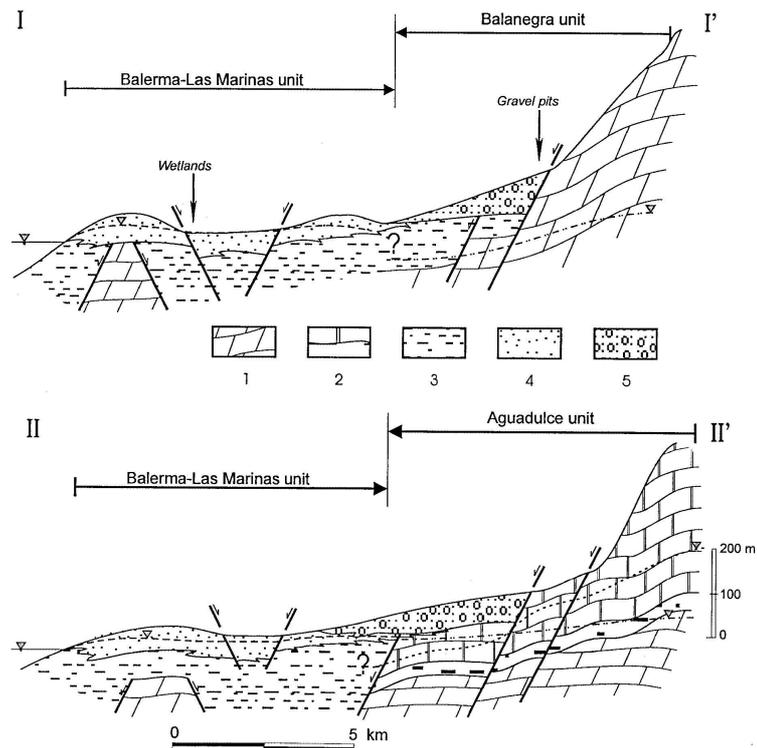


Figura 1 B

Figure 1:A: Site location of studied area with the situation of two cross-sections. Numbered subbasins and principal gravel pits are included (adopted from Pulido-Bosch et al. and al. 2000).
 B: Two representative cross-sections

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No.	Stream	Drainage area km ²	Curve Number CN	Storm depth (mm)	Runoff volume (10 ⁶ m ³)	No. of check dams	Effective volume m ³	Induced recharge %
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	14600	13.5
20	Real	1.4	–	–	–	2	0	0
21	Ancho	5.0	70.2	72	0.06	2	1460	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	5042	11.7
32	El Aguila	10.8	68.9	81	0.15	6	34186	52.5
35	La Maleza	12.4	70.1	80	0.20	5	11860	7.0
42	El Tartell	6.6	74.2	78	0.13	7	8745	7.3
43	Carcáuz	51.5	71.3	85	0.85	20	47090	7.3
44	El Cañuelo	23.3	77.6	83	0.58	17	41880	8.1
47	Vícar	13.4	75.6	79	0.23	13	12095	5.7
50	Las Hortichuelas	19.6	79.8	65	0.39	13	25116	6.5
Totals					2.99	107	203853	100.0

Table 2: General characteristics of the subbasins, distribution cheek dams and results of the simulation. Induced recharge expressed as % of runoff volume (from Martin-Rosales et al., 2007).