

Runoff as an additional water resource
in a semiarid karstic aquifer

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Introduction

General introduction

In arid and semi arid areas, usually, due to the limited quantity of surface water, the only available water resource is provided by ground water. However, the economic and demographic pressures in this area tend to deplete the water resources. Water demand around the Mediterranean basin is growing at an alarming rate. Therefore, there is an urgent need to improve the quantitative assessment of the available water resources which depend on processes by which water will be replenished in order to understand and quantify the recharge rates both in the current conditions and for the future. We will focus on recharge of the aquifer i.e. the transfer of water from the surface to the saturated zone, the aquifers being the part of the saturated zone that hold most of the groundwater.

Like many Mediterranean regions, the Campo de Dalias (Almeria province, southeast Spain) is suffering from large increases in the use of groundwater from its major aquifers. The economic development of Almeria province is astonishing and is primarily based on the growth of the horticultural industry and in second instance on tourism. This region is a prime example of an area where the aquifers are under pressure. Since the 1960s, Almeria province has become the most important region of Europe for horticultural products. Agriculture and its supporting industry constitute the economic driving force in the region. Greenhouses now cover an area of more than 20 000 ha in the Campo de Dalias. Furthermore, the service industry is mainly oriented towards tourism, which is expanding. Gonzalez-Asensio et al. (2003) estimated the annual water use at 140 hm³ for 1999–2000, greatly exceeding the recharge of 50 hm³ given by Pulido-Bosch et al. (1993). Although the aquifer

volume is very large, exploitation of groundwater has already caused environmental problems. The piezometric level has fallen to 30 m below sea level in the western lower aquifer (Gonzalez-Asensio et al., 2003), and some coastal areas suffer from marine intrusions, leading to salinization of groundwater (Pulido Bosch, 1998 ; Pulido Bosch et al., 2000). Hence, the study of the aquifer recharge patterns is of major economical and environmental interest. The EU FP6 Alert-project which deals with an integrated water resources management in the coastal aquifer in the Andarax river basin (Almeria, Spain) draws the same conclusions concerning socio-economic development and impacts on environment i.e. groundwater mismanagement and pollution (Van Cauwenbergh, 2008).

In an attempt to solve the water scarcity, the previous Spanish Government proposed the Spanish National Hydrological Plan (PHN), which intended the long distance transfer of water from the Ebro to the regions in the south east. However, the current government, under pressure from environmentalists, decided to discard this plan. The current Spanish Government has implemented in 2004, the national water plan 'Programa AGUA' "Actuaciones para la Gestión y Utilización del Agua" which means Actions for the Management and Use of Water. The irrigation policy is driven by the European Union (EU) Water Framework Directive and the new adapted text of the water law. Downward and Taylor (2007), explain that to solve water scarcity problems, the programa AGUA is based mainly on desalination plants and on facilities to re-use waste waters. However, this solution is not free of environment impacts such as additional sea water intrusion and to the increase of the carbon footprint. The electricity consumption is predicted to increase by as much as 30 % in Almeria due to the implementation of 5 desalination plants, for Almeria, the total production of desalinized water is expected to reach about 189 hm³/year for a cost estimated at 352 million € (Downward and Taylor, 2007). It should be noted that this region has great potential for solar energy that can possibly be used as an energy source for desalinisation to overcome an environmental problem and reduce the carbon footprint.

Almeria's long-term economic sustainability is based primarily on water resource availability. Focusing research on a better understanding of the recharge system to maintain or increase the volume of the water resource is a priority in this region and more broadly for many semi-arid areas.

Problem statement

Recharge assessment of groundwater defining the rates, the processes and management is generally based on yearly and global estimates. Moreover, karstic aquifers are characterized by a complex heterogeneity of groundwater flow. Several methods are commonly used to estimate the recharge rates such as environmental tracers and isotopes. While numerous uncertainties are linked with recharge estimations, several methods are generally simultaneously used (Scanlon et al., 2006). Beyond the error of the method used, uncertainties can be mainly explained by the rarity of rainfall/runoff events. These variables are difficult to be observed; the monitoring is complex and time consuming. Therefore, approaches used to estimate recharge, are poorly validated. Long term annual average over 6 to 30 years are generally given and are essential to approach the global estimates, whereas it does not allow defining precisely the spatial and temporal distribution and processes of recharge involved which are an unconditional aspect of a sustainable management of the water resource (Hugues et al., 2008; DeVries and Simmers, 2002; Scanlon et al., 2006).

Paradoxically, many authors point to the major influence of extreme event on the recharge rates in semi-arid areas (Summer et al., 2000; Lazaro et al., 2001, Vandenschrick et al., 2002; Martin-Rosales et al., 2007; Hugues et al., 2008). Extreme events are generally considered as storm event or high intensity rainfall whose return period is more than one year. These rainfall events are well-known to be highly variable in space and time, especially in mountainous region (López-Bemúdez and Albadalejo, 1990; Lazaro et al., 2001). Rainfall is

highly seasonal, the bulk of annual precipitation occurs during the winter months and precipitation occurring during the summer months tends to be convective (Mulligan, 1998, Alonso-Sarria et al., 2002). However, extreme events probably dominate the recharge but no evidence exists to suggest that the recharge is limited to this type of events (Darling, 2004). Therefore, research taking into account a finer temporal and spatial resolution is required.

The relationship between rainfall volume of individual events and aquifer recharge has received limited attention. Information on the relative contribution of events to recharge according to their intensity is required since the processes and their spatial distribution also differ. Light events will infiltrate into the soil and most of the water retained will be lost to evapotranspiration. In areas with thin soils or rock outcrops, moderate events (considered as less than 1 year return period) can exceed the infiltration capacity and /or the water holding capacity of the soil. Runoff produced, will most of the time re-infiltrate downslope in zones with higher infiltration capacities (Yair and Raz Yassif, 2004). As long as the soil retains the water, it will be almost completely lost to evapotranspiration. If this lateral flow of water along the hillslope is interrupted, locally the soils will be saturated leading to recharge. Extreme events will saturate the soil in the entire catchment and will produce continuous runoff to the outlet. Under such conditions, a large part of the runoff is lost in the river beds. Snow fall is particularly important for recharge in mountain areas as during melting the soils become saturated and the excess water percolates into the underlying rock. Hence, if the relative contribution of these different types of events to the recharge is known, priorities can be set and measures taken to preserve the most important sources or alternatively to target sources that are under represented under the current land use.

At the river basin scale it is often assumed that runoff is negligible in semi arid limestone mountains, and therefore the contribution of runoff to recharge is not taken into account (Contreras et al., 2008). Although, this statement might be valid at the river basin scale and when assessing the annual water balance, a more detailed consideration of runoff (e.g. flowing from the

steep slopes and infiltrating in the bed of an ephemeral river) both in space and in time can be justified to target preferential recharge zones. From the discussion above it becomes clear that such zones differ from one event to another i.e. from the foot of a hillslope during moderate events to the river network and even the outlet of the catchment during extreme events.

The discontinuous and erratic pattern of runoff has been cited by many authors and explains the difficulties encountered during monitoring of runoff in semi arid areas and even more in predicting rainfall/runoff relationships (Pilgrim et al., 1988; Calvo-Cases et al., 2003; Puigdefabregas, 2005). At the catchment scale, continuous runoff through the outlet is extremely rare (Puigdefabregas et al., 1998; Boix-Fayos et al., 2006). Therefore, research on runoff processes is restricted to more detailed scales. The spatial variability of runoff generation is recognized to be linked to the high spatial heterogeneity of the surface properties. In general, Hortonian overland flow is thought to dominate on hillslopes in limestone areas where due to the permeability of the bedrock, the groundwater very rarely reaches the surface. Nevertheless, saturated overland flow as a result of perched groundwater during long rainy spells or a combination of both runoff types have been reported (Yair, 1992; Martinez-Mena et al., 1998; Boix-Fayos et al., 1998). However, the infiltration, and therefore the surface conditions, becomes the limiting factor to runoff (Bergkamp et al., 1996; Bryan and Yair, 1982; Cerda et al., 1995; Puigdefabregas, 2005; Yair and Lavee, 1985; Lavee et al., 1998). The variability of surface conditions is one of the major challenges, and therefore studies are generally limited to small plots or data obtained by means of rainfall simulations (Arnau-Rosalen et al., 2008) and do not integrate the processes likely to occur at the hillslope scale. Recently, some studies focused on hydrological behaviour of runoff at the hillslope scales (e.g. Bracken & Kirkby, 2005; Western et al., 2001) or attempted to extrapolate results from the plot scale to the hillslope scale (Arnau-Rosalen et al., 2008). The identification of thresholds conditions explaining runoff patterns in function of precipitation quantity clearly improves

the understanding of the hydrological behaviour of these heterogeneous systems (Yair and Lavee, 1985; Puigdefábregas et al., 1998; Calvo-Cases et al., 2003; Cammeraat, 2004). However, further improvement in defining i) the areas with a similar hydrological behaviour, ii) the climatic and edaphic conditions under which runoff is produced and iii) the connectivity through the outlet is necessary for extrapolating the runoff processes understanding at the plot scale to the catchment.

Boix-Fayos et al. (2006) pointed to the difficulties encountered when extrapolating data, observations and processes from a smaller plot to a larger area, and concluded that direct linear extrapolation is not realistic for a semi arid area. Hence, the hydrological response at the outlet of small catchments is difficult to predict (Calvo-Cases et al., 2003; Bracken et al., 2005; Croke et al., 2005). However, correct estimates are needed both when runoff is used as an additional source of surface water (e.g. collected in water harvesting systems; van Wesemael et al., 1996) and when runoff is considered as a more effective way to recharge the groundwater. It has been shown that patterns of surface properties (Arnau-Rosalén et al., 2008 and Calvo-Cases, 2005) and more precisely vegetation cover (Puigdefábregas, 2005) explain to a large extent the runoff behaviour at the hillslope scale. Most studies use hydrological response units or in other words spatial units where the runoff generation processes are similar (Imeson et al., 1992; Yair, 1992; Cerda et al., 1995; Bergkamp et al., 1996; Cammeraat, et al., 2004).

As explained in the previous paragraph, it is difficult to determine the contribution of runoff and identify the zones where recharge preferentially occurs in limestone mountains. (Pulido-Bosch et al., 1993; Pulido-Bosch, 1998; Vallejos et al., 1997; Molina et al., 2002). However, in semi-arid and arid areas, deep percolation of surface water is restricted to certain conditions, as the water retained in the soil after light to moderate rainfall is quickly lost by evapotranspiration. Therefore, surface runoff that concentrates water in a

limited area is much more likely to percolate. Recent studies focus on stream beds as sites where recharge preferentially occurs (DeVries and Simmers, 2002, Coes and Pool, 2005; Lange, 2005; Scanlon et al., 2006; Callegary et al., 2007). Although, quantitative estimates of the percolation in such stream beds are limited (Lange, 2005, Mudd et al., 2006).

Modelling approaches are attractive for the management of water resources as the impact of several factors influencing the hydrological behaviour can be tested. Hence, models have to realistically represent the heterogeneity of the hydrological response in semi arid mountain ranges and distributed models seem more appropriate in this case. However, the choice of a model is mostly restricted to the available data. Some of the main problems in obtaining the data at a high spatial and temporal resolution are i) contrasting seasons inducing variation in antecedent conditions, ii) large spatial variation of rainfall characteristics during an event and iii) the heterogeneity of surface properties. Quantifying the spatial distribution of runoff and recharge is essential and therefore the understanding of the relation between runoff generation on the hillslopes and percolation in the stream bed response is essential. Such an approach will increase our understanding of the contribution of runoff as additional water resource both at the hillslope and at the catchment scales.

Objectives of the thesis

The overall aim of the thesis is to evaluate the role of runoff as a water resource in a semi-arid limestone mountain range. This thesis intends to approach the groundwater recharge system through an improved understanding of recharge rates in function of precipitation characteristics and spatial patterns of runoff processes. This thesis focuses on runoff as a component of water balance at the event scale which is generally regarded as negligible in the

recharge system in semi-arid areas. The research is carried out in the large karstic aquifer of the Sierra de Gador – Campo de Dalias located in Almeria province (southeast Spain).

The main aim is broken down into four specific objectives:

- Define the type of the rainfall events that preferentially recharge the groundwater.
- Identify the controlling factors for the production of runoff on hillslopes as a function of the spatial heterogeneity of soil properties.
- Predict runoff generated on the hillslopes in order to evaluate their effectiveness to collect runoff and to validate an expert based hydrological model.
- Estimate the contribution of the runoff to recharge at the catchment scale by extrapolating the rainfall/runoff model previously calibrated and validated on hillslopes.

Outline of the thesis

Most of the chapters are based on articles published in international peer-viewed journals.

The study area is introduced in the first chapter, where the geological and hydrological setting of the Sierra de Gador is presented, and the climate is broadly described.

Chapter 2 addresses the first specific objective and gives a type of storms according to their contribution to recharge. The method uses stable water

isotope analysis of precipitation (both in the Mediterranean basin and in the Iberian peninsula) and groundwater from springs and boreholes in the study area. The main assumption in this chapter is that the deuterium excess can be used as an indicator of the origin of the water vapour producing the storm. The isotopic data in the Mediterranean basin are compared with data from aquifers of the study area to explain the origin and type of precipitation events dominating recharge.

Chapter 3 addresses the second specific objective and is dedicated to the analysis of rainfall and runoff data monitored during seven years in four water harvesting systems draining hillslopes and small catchments of different sizes. The substantial dataset allows assessing rainfall characteristics, soil surface properties which have a major influence on runoff processes.

Chapter 4 addresses the third specific objective. It focuses on an adaptation of an expert based rainfall/runoff model to a semi-arid area. The hydrological model is used to calibrate and validate the runoff in three water harvesting systems in order to test the effectiveness of these systems. The spatial patterns of landscape units of low infiltration and the overall vegetation cover are significant to predict runoff.

The extrapolation to larger areas, based on the latter results is presented in chapter 5, addressing the fourth specific objective. Earth observation data and spatially distributed rainfall data are used for the parameterization phase. The hydrological model is used to simulate runoff generated in a catchment of 26 km² in order to predict the quantity and propagation distances of the runoff. The main zones of runoff generation are identified but also the contribution of runoff reaching the stream-beds and subsequently percolating to the groundwater is identified and mapped. Finally, the contribution of runoff to concentrated recharge and its spatial pattern are compared to the results of other studies using independent methods to estimate recharge.

Finally, chapter 6 gives a synthetic view of the most important findings of this thesis. These findings open up perspectives for targeted management of the recharge in the important aquifer of the Sierra de Gador-Campo de Dalias

and by analogy to similar karstic aquifers around the Mediterranean. The perspectives for further research are also discussed.

Chapter 1

Study area

1.1 Localisation

The Sierra de Gador and the Campo de Dalias are located in Almería province, southeastern Spain. The Adra and Andarax rivers enclose an area of 650 km². The Sierra de Gador is a mountain range, reaching 2242 m asl and the Campo de Dalias is the connected coastal platform which is running parallel to the coast. The Sierra de Gador belongs to the Alpujarride complex of the internal areas of the Cordillera Betic system (Fig. 1.1).

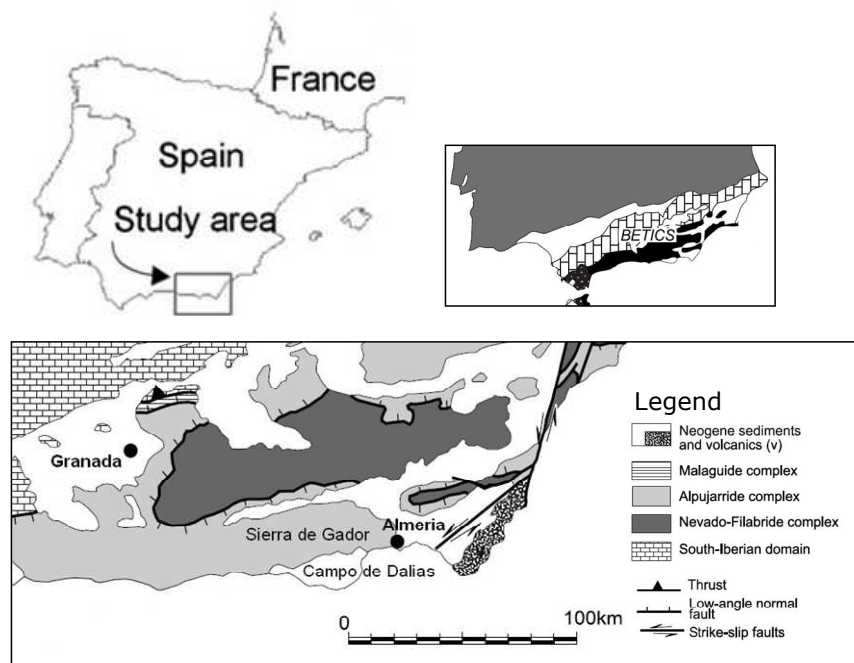


Figure 1.1. Localisation of the study area and regional tectonic setting and structural map of the central and eastern Betics (adapted from Booth-Rea et al., 2004).

1.2 Geological and hydrogeological setting

Several authors have discussed the complexity and the scale of the recharge system of the Campo de Dalias and the carbonate mountain range of the Sierra de Gador aquifers (Pulido-Bosch et al., 1993; Vallejos et al., 1997; Pulido-Bosch, 1998; Dominguez-Prats, P, 2000; Molina et al., 2002; Gonzalez-Asensio et al., 2003). The most important hydrogeological units in the study area consist of several aquifer formations superimposed mainly constituted by Permian and Triassic Alpujarride carbonate rocks (pre-orogenics) , Miocene and Pliocene calcarenites (post-orogenics) (Pulido-Bosch et al., 1993; Pulido-Bosch et al., 2000) (Fig. 1.1 and Fig. 1.2).

The aquifer units of the Sierra de Gador and the Campo de Dalias consist mainly of carbonates rocks of the Gador and Felix units that belong to the Permian and Triassic Alpujarride Units (Fig. 1.2). The Gador unit widely represented comprises a sequence of thick carbonates resting on metapelites. Overlying the latter, the Felix unit consists of a carbonate member that also presents a basal metapelite member (Vallejos et al., 1997). These two tectonic units are highly permeable, fractured, fissured and karstified. On the top of the Alpujarride materials lie the aquifer units of the Miocene and Pliocene calcarenites. The latter is widely represented into the Campo de Dalias and consists of a basal conglomerate and a marl formation, which form the impermeable part of this unit (Pulido-Bosch et al, 2000). The Quaternary alluvial fans are permeable. Most authors agree that the water-bearing formations are hydrologically connected to the aquifer units of the Campo de Dalias (Vallejos et al., 1997, González-Asensio et al., 2003). Recharge to the Campo de Dalias carbonate aquifers occurs through infiltration of precipitation in the Sierra de Gador and in the Campo de Dalias itself (Pulido-Bosh et al., 2000). However, the Pliocene calcarenites have become disconnected with the increased exploitation of the groundwater system (Pulido-Bosch et al., 1993; Vallejos et al., 1997).

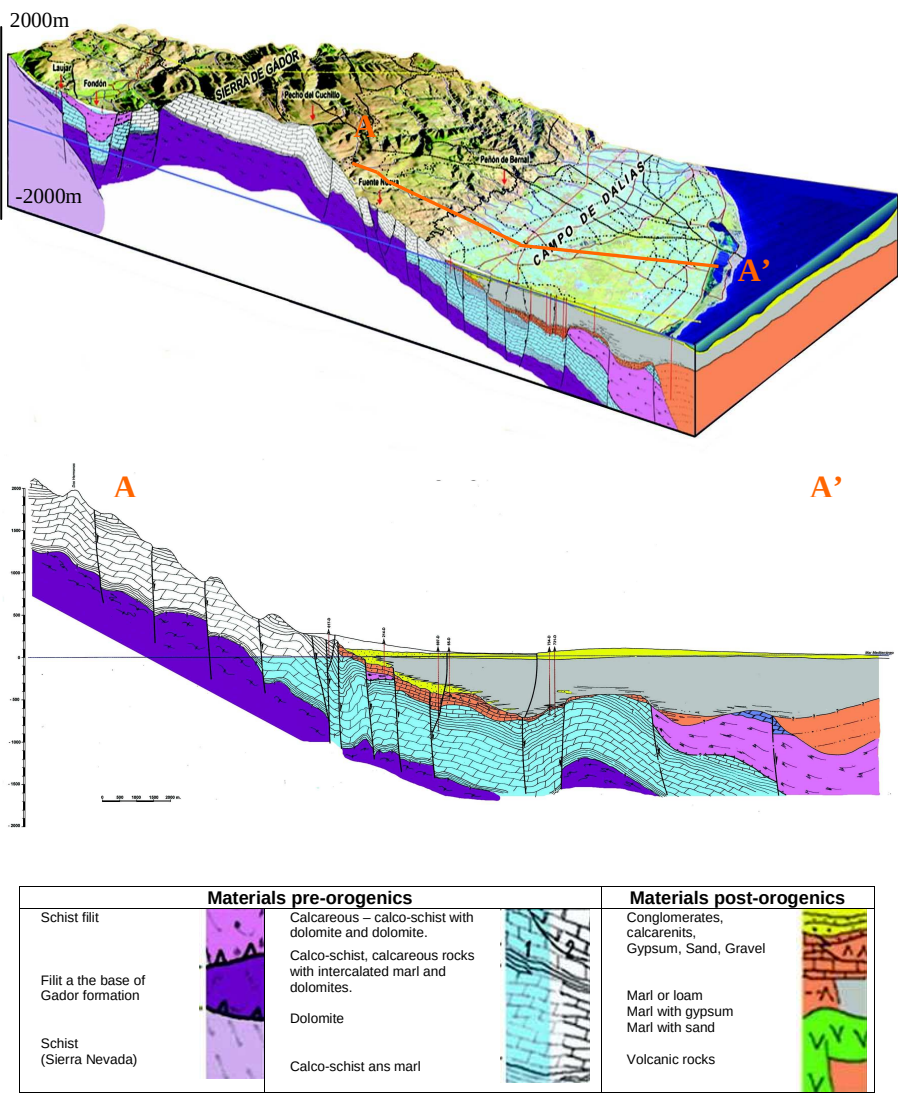


Figure 1.2. Geology and hydrological units of the study area. 1: Saturated zone; 2: Unsaturated zone (Dominguez-Prats., 2000).

Radiocarbon dating of these aquifers gave estimates of generally long residence times of about 1000 to 2000 years (Vallejos et al., 2003). Pulido-Bosh et al. (1993) have shown that the geology of the area is complex and that discontinuities are abundant. Vallejos et al. (2003) suggests there may be two types of recharge to the aquifer, one modern with a fast flow and the other much older, which forms the reserve of the aquifer. They estimate by using

tritium contents that the modern recharge (after 1953) represents 10 % of the total aquifer volume. Given the large volume of the aquifer and its recent exploitation, the recharge volume still is an important factor in the overall aquifer budget. Since the economic development of the region heavily depends on the aquifer exploitation, it is crucial to understand the conditions under which the recharge can be improved.

1.3 Soils

Rendzic or Mollic Leptosols, Kastanozems, Phaeozems, Cambisols and Regosols are soil groups in the classification system of the Food and Agriculture Organization (FAO) present in the Sierra de Gador. The degraded soils on the hillslopes are mainly Leptosols and Phaeozems in the Sierra. The Leptosols are especially susceptible to erosion and the thickness is less than 50 cm depending on their location on the slope. The deeper soils which were protected from erosion can be classified as Luvic Phaeozems and Calcaric Phaeozems (organic matter: $2.3 \pm 1.3\%$, ICONA-CSIC, 1988 and clay content: 30-50 %, Li et al., 2007 and Moreno, 2005). This soil is mostly present between 1200 to 1500m and developed on calcareous and dolomite rocks (Contreras, 2006).

1.4 Climate

The study area is characterised by a semi-arid climate with an average annual precipitation of 196 mm in Almeria (from 1971 to 2000) to about 670 mm on the summit of the Sierra de Gador resulting from a marked altitudinal gradient of 23 mm per 100 m (Contreras et al., 2006). Precipitation is also characterized by strong seasonal variation with distinct wet and dry seasons with a maximum in autumn and a minimum in July and August (Lazaro et al., 2001; Trigo et al., 2004). The climate is marked by a high intra- and inter-annual variability. The annual precipitation distribution is seasonal due to changes in the atmospheric circulation centres. During the warmer part of the year, from

May to September, the region is under the influence of relatively high pressure, which inhibits precipitation in the area. During the cooler months between October and April, surface pressure is generally reduced, allowing more frequent incursions of precipitation producing weather systems. The months of July and August are almost completely dry, but the period October-February is humid due to incursions of active Atlantic frontal systems (Summer et al., 2000). In the area of Almeria the significance of severe thunderstorm development during September and October produces an autumn peak in precipitation (Summer et al., 2000; Lazaro et al., 2001).

Precipitation in Spain has two sources: the Mediterranean basin and the Atlantic Ocean. Alonso-Sarria et al. (2002) explained that the dynamic origins of storms over the Iberian coast are related to the global atmospheric circulation modified by geographic factors. Due to its latitudinal position, the Mediterranean basin receives precipitation generated by frontal depressions related to western Atlantic flows, as well as convective storms associated with eastern flows and cyclogenetic processes in the Mediterranean basin itself.

The annual mean temperature is 18.7 °C in Almeria (min: 12.5 °C and max: 30.7°C). Rainstorms of short duration and high air temperatures during, or immediately after, rainfall contribute to the significance of evaporation losses. The evaporation losses yearly may account for 30-85% of the annual precipitation in semi arid regions (Pilbeam et al., 1995). For the study area, Pulido-Bosch (1998) and Contreras (2006) confirmed this significant loss by evaporation at around 70 % of the annual precipitation.

It is to be noted that at the beginning of the study, meteorological stations were not common on the Sierra de Gador and long term data were not available. The study area begins to be well equipped and a better description of the climatic conditions will be available. Additional information about the climate and precipitation in the Sierra de Gador range will be provided in the following chapters.

1.5 Vegetation

Three vegetation belts mainly composed of Mediterranean shrub and matorral species were identified in the Sierra de Gador (Mota, 1990 and Carrión et al., 2003). The Thermomediterranean belt occurs below 800m asl, and is characterized by species rich communities (e.g. *Pistacia lentiscus*, *Chamaerops humilis*, *Quercus coccifera*). The Mesomediterranean belt ranges from 800 m to 1400 m asl and is characterized by species of *Genista*, *Ulex parviflorus*, *Asparagus acutifolius*, *Phlomis purpurea* and *Lavendula lanata*. Above 1400 m, the Supramediterranean belt is dominated by shrubs, herbaceous vegetation, rare oak (*Quercus rotundifolia*, *Quercus faginea*) and pine (*Pinus halepensis*, *pinus nigra*) trees. Open shrubland and gramineous steppes occur on the little disturbed hillslopes, and chamaephytic steppes on the heavily grazed alluvial fans (van Wesemael et al., 1998 and Valladares et al., 2005).

Since Roman times, the forest is in decline and the current vegetation in the Sierra de Gador is quite recent (Carrion et al., 2003). Lead mining since 1822, had a major impact on tree cover with the consequence of total deforestation and severe degradation by rapid erosion of the fertile soils. Nowadays, bare surfaces, thin soils and rock outcrops dominate the landscape. Large reforestation programmes were started in Spain at the beginning of the 20th century and coincided with the rural crisis and the abandonment of the countryside, which was re-colonised by Mediterranean species. The presence of coniferous trees is largely due to the reforestation programme (Giménez, 2000).

1.6 The socio-economic context

The accessibility to water resources has mainly driven the economic development of Almeria province. The access to groundwater was made possible with the evolution of means of water extraction and innovations in agricultural technologies which convert uncultivated areas to highly productive areas. Traditional and rural agriculture located generally on the slopes terraces to cultivate grape, olives, cereals and almonds has been slowly been replaced by

irrigated agriculture and horticulture in greenhouses (Orgaz et al., 2005). The enormous expansion of this type of agriculture: low-cost, unheated plastic-covered structures and with soil-grown crops starts in the 1960s (Mota et al., 1996; Orgaz et al., 2005) and reaches nowadays, in the Campo de Dalias, a total surface of 20,000ha, transforming a poor region, also as a result of the end of mining activities to a thriving region. The development of transport networks which are in phase with the development of the greenhouses promotes tourism. While the region of Andalusia has a population growth of 13% between 1996 and 2008, Almeria for the same period shows the strongest growth with 33% (INE, 2009).

Chapter 2

Origin and type of rainfall for recharge of a karstic aquifer in the western Mediterranean, a case study from the Sierra de Gador-Campo de Dalias (south-east Spain)¹

Outline

Isotope signatures in precipitation from the Global Network for Isotopes in Precipitation (GNIP) around the Mediterranean basin and literature data are compared to isotopic data from a large karstic aquifer in southeast Spain to explain the origin and type of the precipitation events dominating recharge. Analysis of the deuterium excess d at the scale of the Mediterranean basin and at the regional scale allows us to understand the isotopic context of the study area: Campo de Dalias and the Sierra de Gador (Almería province). The origin of precipitation can be determined from its d value. The d value changes as a function of the initial evaporation condition. It depends on the relative humidity and temperature during the evaporation producing the water vapour of the clouds. The water vapour, which dominates the study area is generated in two areas, the Atlantic Ocean ($d = 10\text{‰}$) and western Mediterranean basin ($d = 15\text{‰}$). With increasing precipitation volume the western Mediterranean character dominates. These heavier storms contribute mainly to recharge, as illustrated by the d value of 13.6‰ in deep groundwater of the Campo de Dalias. Weighted d values increase with the volume of

¹ This chapter is based on an article by Frot, E., van Wesemael, B., Vandenschrick, G., Souchez, R., Sole-Benet, A., 2007. Origin and type of rainfall for recharge of a karstic aquifer in the western Mediterranean: a case study from the Sierra de Gador-Campo de Dalias (southeast Spain). *Hydrological Processes* 21, 359-368. doi: 10.1002/hyp6238.

precipitation giving a significant relationship for the southern and eastern coast of the Iberian Peninsula. This selectivity of d to monthly precipitation was used to estimate the return period of precipitation leading to aquifer recharge at 0.9-4.9 years. Still moderate rainfall, which occurs more frequently, represents c. 60-90% of the total precipitation. One of the challenges to meet ever-growing water demands is to increase recharge from moderate events yielding intermediate quantities per event, but forming the bulk of the annual precipitation.

2.1 Introduction

In the Mediterranean region, stable water isotopes (δD and $\delta^{18}O$) have often been used to understand the recharge of aquifers (Bajjali et al., 1997; Tantawi et al., 1998; Nativ et al., 1999; Maliki et al., 2000; Longinelli et al., 2003; D'Alessandro et al., 2004). The deuterium excess ($d = \delta D - 8\delta^{18}O$) reflects the relative humidity and the air temperature of the region where the evaporation leading to rainfall occurred (Gonfiantini, 1996; Jouzel, 1986; Vandenschrick et al., 2002). In regions with contrasting origins of precipitation, d value could be link with weather patterns, which generated the precipitation. According to the relation existing between ^{18}O and deuterium, the deuterium excess could also be used to determine the origin of precipitation and in which proportion rainfall from different origins contribute to recharge of the aquifer (Vandenschrick et al., 2002; Lee et al., 1999; Shivanna et al., 2004; Yamanaka et al., 2002). For instance, Shivanna et al. (2004) use environmental isotopes and injected tracer techniques for the estimation of the contribution of storms and total annual precipitation to groundwater recharge, in the semi-arid region of Bagepalli, Kolar district, Karnataka (India). Studies focusing on the western Mediterranean are still limited (Cruz-San Julian et al., 1992; Vallejos et al., 1997; Celle-Jeanton et al., 2001a, b; Vandenschrick et al., 2002; Darling, 2004). However, in the western part of the Mediterranean basin, there is a clear distinction in the isotopic signatures of the precipitation produced by Atlantic and Mediterranean weather systems (Celle-Jeanton et al., 2001a; Lazaro et al., 2001). These studies directly link the isotopic signature of the precipitation to the prevailing weather conditions during the rainfall event. In the western Mediterranean the groundwater has an isotopic signal reflecting a Mediterranean origin of the precipitation (Vallejos et al., 1997; Celle-Jeanton et al., 2001a; Vandenschrick et al., 2002). Precipitation of Mediterranean origin often occurs during heavy thunderstorms preferentially in autumn (Summer et al., 2000; Lazaro et al., 2001). However, the relationship between rainfall volume and its isotopic signal, has only received limited attention and no

evidence exists to suggest that aquifer recharge is limited to extreme events (Darling, 2004).

The objective of this chapter is then to better define the recharge patterns of karstic aquifer by using the regional isotopic signal of precipitation, to demonstrate the occurrence of preferential recharge during heavy rainfall and to determine a threshold to characterise such events. The large karstic aquifer of the Sierra de Gador – Campo de Dalías (southeast Spain) is used as a case study.

2.2 Methodology

2.2.1 Water stable isotopes

In this chapter all isotope concentrations are given in δ -units calculated with respect to VSMOW (Vienna Standard Mean Ocean Water) expressed in part per mil (eq. 2.1).

$$\delta_{\text{sample}} (\text{‰}) = 1000 \left[\frac{R_{\text{sample}} - R_{\text{VSMOW}}}{R_{\text{VSMOW}}} \right] \quad 2.1$$

where R_{sample} and R_{VSMOW} are the isotopic ratios of the sample and of the VSMOW respectively.

Moreover, the understanding of the origin of precipitation in the western Mediterranean basin should be improved using the deuterium excess (d) as a tracer for evaporative regions conditions (eq. 2.2).

$$d = \delta\text{D} - 8\delta^{18}\text{O} \quad 2.2$$

If evaporation rates are high during the formation of the water vapour, because of high temperature and low relative humidity of the atmosphere, there is a strong kinetic isotopic effect, and d values are high (Jouzel and Merlivat,

1984). d is usually considered as a more or less conservative property of the part of the atmospheric water cycle associated with water vapour formation by evaporation below cloud level (Ciais and Jouzel, 1994). d is not influenced by transpiration of the vegetation and d value of soil water is the same as that of the precipitation that wetted the soil (Souchez, 2000). It has been demonstrated that the d value is a reliable parameter to determine the precipitation origin (Lee et al., 1999; Vandenschrick et al., 2002; Yamanaka et al., 2002).

In this chapter, isotope signatures in precipitation from the Global network of isotopes in Precipitation (GNIP; IAEA, 2004) and literature data are compared with isotopic data from aquifer of the study area to explain the origin and type of precipitation events dominating recharge. The GNIP provides a world-wide survey of the isotopic composition of monthly precipitation. The yearly weighted mean d values were calculated to understand the context of the study area within the Mediterranean basin. 47 GNIP stations around the Mediterranean basin were selected in function of their location (Table 2.1). In order to compare different stations the monthly isotope data were selected from those stations with a minimum record period of five years. Data from the summer months (June to September) receiving less than 10 mm were excluded, since these are likely to be influenced by evaporation during sample collection (Celle-Jeanton et al., 2001b).

2.2.2 Statistical treatment

Two parameters were used to evaluate whether there is a systematic relationship between monthly rainfall and its d value. First, the mean d values (d_k) weighted by the volume of rainfall (p) in mm for all months below a given rainfall depth (x) in mm were used (eq. 2.3). These weighted means were calculated for rainfall depth intervals increasing by 25 mm to the maximum monthly rainfall recorded in the station.

$$d_x = \frac{\sum_0^x (d p)}{\sum_0^x p} \quad 2.3$$

Second, the mean d values (d_s) weighted by the volume of rainfall (p) in mm for all months above a given rainfall depth (s) were used (eq. 2.4). These weighted means were calculated for rainfall depth intervals starting from the maximum monthly rainfall and decreasing by 25 mm.

$$d_s = \frac{\sum_{s \max}^{s \min} (d p)}{\sum_{s \max}^{s \min} p} \quad 2.4$$

Hence, the d values weighted by monthly precipitation volume can be calculated for all months either below or above a threshold using eqs. 2.3 and 2.4.

In order to detect regional trends in d values with precipitation, the latter had to be standardised across sampling stations. For the weighted d values below a threshold (eq. 2.3) the standardised rainfall depth (r_s) was defined as the rainfall depth intervals (increasing by 25 mm to the maximum monthly rainfall recorded in the station) divided by the long-term mean annual rainfall of each sampling station. For the weighted d values above a threshold (eq. 2.4), which reflects the importance of extreme events, the index for extreme events I_e is defined as the rainfall divided by twice the long-term rainfall of the rainiest month (Conte et al., 2002).

A non linear regression model was used to describe the relationship between d_s value and r_s :

$$y = c - a * e^{(-bx)} \quad 2.5$$

where c is the weighted mean of d values for the station (%), a is the difference between the weighted mean of d values for the station and the value of d for x values tending to zero and b is a fitting variable (Eq. 2.5).

The performance of the sited non-linear relationships was assessed by the root mean square error (RMSE) (Eq. 2.6).

$$RMSE = \sqrt{1/n \sum_{i=1}^n (y_i - \hat{y}_i)^2} \quad 2.6$$

where y_i is the i^{th} observed data and $\hat{y}_i$ is the i^{th} modelled data of n observations.

The relationship between d_x and I_e was initially described with a linear regression. However, given that the Durbin-Watson test was not able to prove the absence of autocorrelation, an autoregressive model of first order AR (1) was used (Eq. 2.7). Furthermore, the linear regression was corrected for autocorrelation using the SAS statistical package (SAS Enterprise Guide). The highest values are based on a minimum of three monthly values.

$$X_t = c + \phi X_{t-1} + \varepsilon_t \quad 2.7$$

where ϕ is the parameter of the model, c is a constant and ε_t is an error term.

The return period R (years) of the monthly rainfall was calculated for the meteorological station of la Zarba from long-term data covering the period 1961 to 1995 according to (Eq. 2.8):

$$R = \frac{n+1}{r} \quad 2.8$$

where n is number of years on record and r is the rank of the event being considered. Due to the strong precipitation gradient with altitude in the Sierra de Gador-Campo de Dalias aquifer system, the meteorological station of La Zarba situated in the middle of the altitudinal range of the Sierra de Gador (1210 m a.s.l) is considered to be representative for precipitation data of the whole study area.

Table 2.1. Weighted annual averages of d-values, period of measurement, number of records, annual rainfall (1961-2001) for selected coastal stations of the Mediterranean basin. Data extracted from GNIP yearly 2001, IAEA (2004).

SampleSite	Latitude ¹	Longitude ²	Altitude (m)	Measurement period	Records ³ (years)	Annual Rainfall (mm)	Weighted Mean d-values (‰)
PORTO	41.08	-8.36	93	1989-1999	8	1163	10.5
FARO	37.01	-7.96	9	1979-1997	14	518	11.5
BEJA	38.01	-7.52	246	1989-1990	2	747	10.8
VILA REAL	41.19	-7.44	481	1989-1990	2	986	9.1
PENHAS DOURADAS	40.25	-7.33	1380	1989-1998	9	1434	14.1
PORTALEGRE	39.17	-7.25	597	1989-1999	10	829	12.7
BRAGANCA	41.48	-6.44	690	1989-1990	2	784	11.6
CACERES TRUJILLO	39.47	-6.33	405	2000-2001	2	590	6.8
MORON BASE SEVILLA	37.15	-5.62	88	2000-2001	2	591	12.9
GIBRALTAR	36.15	-5.35	5	1962-2001	22	721	12.0
FES SAIS	33.58	-4.59	571	1994-2000	4	386	12.7
ALMERIA AEROPUERTO	36.85	-2.38	21	2000-2001	2	182	11.9
MURCIA	38.00	-1.17	62	2000-2001	2	287	10.1
TORTOSA	40.82	-0.48	48	2000-2001	2	496	10.1
VALENCIA	39.47	-0.38	13	2000-2001	2	477	8.9
BARCELONA	41.38	2.12	65	1985-1991	7	549	11.9
PALMA DE MALLORCA	39.55	2.62	3	2000-2001	2	311	9.0
GERONA AEROPUERTO	41.90	2.75	129	2000-2001	2	562	6.9
ALGIERS-CN	36.78	3.05	180	1999-2001	3	581	5.6
MONTPELLIER	43.57	3.95	45	1997-1998	2	524	10.6
AVIGNON	43.95	4.82	30	1997-2001	5	540	8.5
GARDANNE	43.45	5.45	215	1997-1998	2	347	11.3
CARPENTRAS	44.95	5.78	99	1997-1998	2	425	6.1
MALAUSSENE	43.92	7.13	359	1997-1998	2	523	12.5
MONACO	43.70	7.50		1999-2001	3	661	4.5
GENOA (SESTRI)	44.42	8.85	2	1962-2001	27	1051	10.0
TUNIS (CARTHAGE)	36.83	10.23	4	1969-1995	18	483	9.7
PISA (CENTRAL)	43.71	10.40	12	1993-2001	5	838	10.8
SFAX	34.43	10.41	23	1993-2001	8	213	9.4
SAN PELLEGRINO IN AL	44.18	10.42	1520	1993-2001	4	1979	13.7
BRASIMONE	44.09	11.08	842	1971-1986	5	907	14.2
BARI	41.10	16.87	50	2000-2001	2	215	10.8
ATHENS (HELLINIKON)	37.90	23.73	27	1962-1972	3	429	13.4
SIDI BARRANI	31.62	25.95	24	1979-1996	12	143	12.4
RHODES (MARITSAI)	36.38	28.10	42	1964-1972	3	667	18.4
KOZAGAC (AYDIN)	37.03	29.39	610	1987-1991	2	397	12.6
ALEXANDRIA	31.18	29.95	7	1962-1994	13	222	16.4
KOCBEYLI (ISPARTA)	37.45	30.33	1025	1990-1992	3	481	12.4
ANTALYA	36.88	30.70	49	1966-2001	24	1049	17.0
GUZELOLUK (ICEL)	36.54	34.07	1400	1990-1991	2	489	17.0
BET DAGAN	32.00	34.82	30	1961-2000	19	513	18.1
ADANA	36.98	35.30	73	1979-2001	20	652	15.4
HAR KNA'AN	32.97	35.50	964	1976-1988	7	653	22.2
SHOUBAK	30.27	35.58	1300	1966-1967	2	239	22.4
RAS MUNEEF	32.37	35.75	1150	1990-1998	3	617	22.5
AMMAN-WAJ	31.96	35.85	900	1990-2001	4	348	23.1
AMMAN AIRPORT	31.98	35.93	850	1966-1968	3	316	24.8

¹ Latitude in decimal degrees north of the Equator.

² Longitude in decimal degrees, negative values west of Greenwich, positive values east of Greenwich.

³ Number of years for which data are available.

2.3 Results and discussion

2.3.1 Isotopic signature of precipitation in the Mediterranean basin

The weighted annual mean d values of precipitation recorded in GNIP stations within the Mediterranean basin show a distinct spatial pattern (Fig. 2.1). They increase from the Atlantic Ocean to the eastern extremity of the Mediterranean basin. The western region, stretching from Portugal to Italy, is characterised by d values not exceeding 13 ‰. The eastern zone from Greece to the Middle East shows d values, which reach more than 20 ‰ (Table 2.1, Fig. 2.1). This spatial pattern can be attributed to the origin of the water vapour in the rain bearing clouds. The Mediterranean is a classic example of a closed reservoir subjected to strong evaporation and, therefore, producing water vapour impoverished in heavy water isotopes. The high d values are explained by the relative enrichment of deuterium compared to the heavier ^{18}O referred to as the kinetic isotopic effect (Gat and Carmi, 1970; Araguas-Araguas et al., 2000). The d values of more than 20‰ in the eastern Mediterranean indicate that precipitation is predominantly derived from Mediterranean air masses. The lower d in the western part of the Mediterranean basin is between 10‰ and 15‰ and falls between typical values for water vapour of Atlantic origin ($d=10‰$), and the eastern Mediterranean represented with $d=22‰$ (Gat and Carmi, 1970, Celle-Jeanton et al., 2001a; Vandenschrick et al., 2002). The western part of the Mediterranean basin can be considered as a mixing zone where precipitation originates from water vapour with either an Atlantic or a Mediterranean source area.

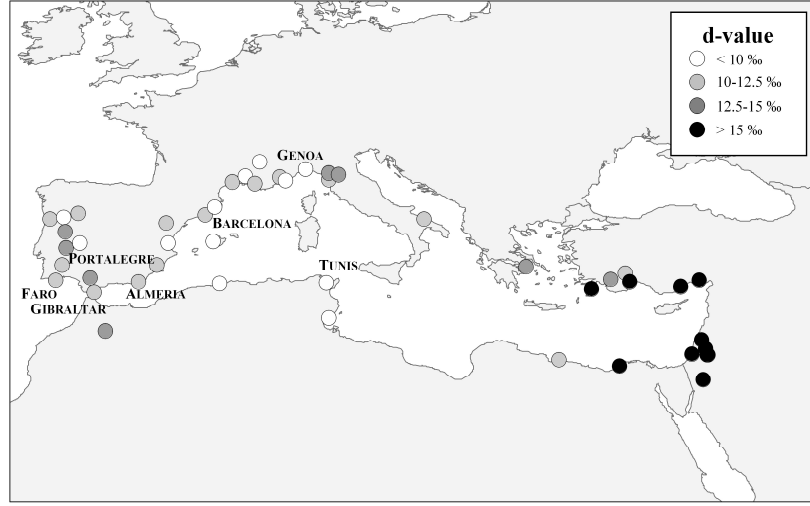


Figure 2.1. Weighted annual mean d -values from coastal stations monitored by the GNIP network around the Mediterranean basin. Data extracted from IAEA (2004).

The GNIP database does not provide isotopic signatures for individual events, since the samples are aggregated on a monthly basis. However, monthly d values can improve the temporal resolution compared to the weighted annual d values over the recording period. Therefore, the weighted mean monthly d values will be used to determine whether a relationship exists between the origin of the water vapour and the amount of precipitation (eq. 2.3 and eq. 2.4). Six stations in the western Mediterranean with an important data set were selected. For Portalegre, Faro, Gibraltar, Barcelona, Genoa and Tunis an exponential model (eq. 2.5) describes the increase in d values with rise in precipitation depth rather well for Fig. 2.2. Monthly rainfall with a Mediterranean origin (i.e. with a high d value) corresponds generally to a larger precipitation volume and an enriched O^{18} (Celle-Jeanton, 2001a). Meanwhile deviations from the general trend within the western Mediterranean occur as a result of variation in the dominant climate system. Although Portalegre is close to the Atlantic Ocean, it nevertheless has the d values with a $d_{x\max}$ value of around 13‰. Whereas Genoa and Tunis on the Mediterranean coast have lower d value with a $d_{x\max}$ value of about 10‰. In contrast to Tunis, the d_x

values in Genoa quickly increase to reach their maximum. Some month with heavy rainfall in Tunis have a low d value, and only the more extreme one had a higher d value. It is clear that the d_x values of the three stations closest to the study area, Gibraltar, Faro and Barcelona, follow the same trend (RMSE = 0.38‰) and their $d_{x_{\max}}$ value is about 12‰. Portalegre, Genoa and Tunis are probably not included in the same climatic system. The isotopic record in Almeria is too short with only 2 years of data, to detect a significant trend. However, it can be assumed that the d values for Almería correspond to those of the three closest stations. The study area was therefore considered to be dominated by the weather systems of the south-eastern coast of the Iberian peninsula represented by the GNIP Stations of Faro, Gibraltar and Barcelona.

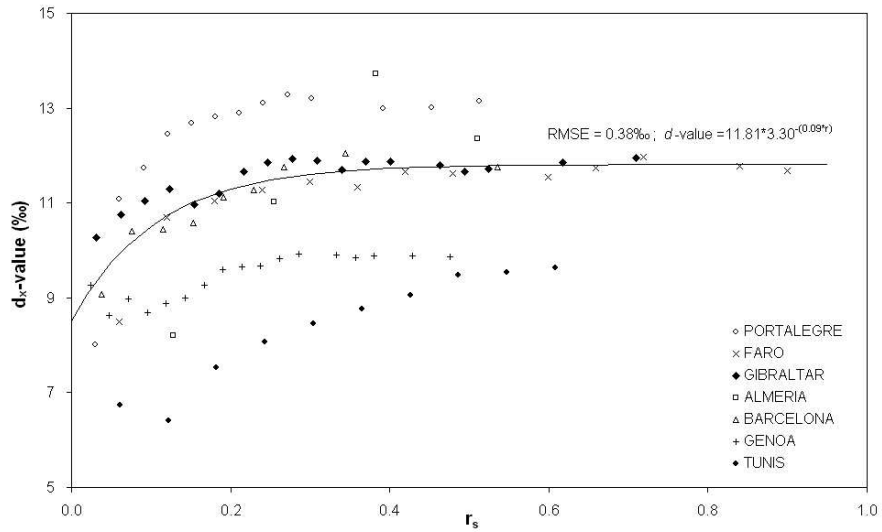


Figure 2.2. Weighted mean d_x -value (eq. 2.3) in monthly rainfall versus standardised rainfall depth (r_s) from six coastal GNIP stations on the Iberian peninsula coast. Data extracted from IAEA (2004). r_s equals rainfall depth divided annual rainfall for each station. The $d_{x_{\max}}$ equals the weighted mean d -value for one considered station (see table 2.1)

2.3.2 Isotopic signature of extreme events along the coast of the Iberian peninsula

The increase of monthly d values with increasing precipitation, described above, is in agreement with the dominantly Mediterranean origin of extreme events (Alonso-Sarria et al., 2002). However, it is quite rare for these events to occur in the same area within the recording period of GNIP stations. For the period of January 1914 to August 1996, 40 extreme events were recorded for the regions of Catalonia, Valencia, Murcia, Balearic Islands and Andalusia (Lopez Bermudez and Romero Diaz, 1993; Poesen and Hooke, 1997). Most of these events occurred in October and November and a reconstruction of the weather pattern of eight events revealed that only one of these storms had an Atlantic origin, the remainder being derived from the Mediterranean (Alonso-Sarria et al., 2002; Table 2.2). However, these events are the result of weather systems dominating the Iberian peninsula and its Mediterranean coast. Hence, they occur at least in an entire coastal region, and half of them even cover two or three coastal regions, from Catalonia in the north-east through Murcia and Valencia to Andalusia in the south. Due to the limited number of GNIP stations (Gibraltar and Barcelona) and the erratic record in Barcelona, only five months with extreme rainfall ($I_e > 0.8$) coincide with extreme events reported in the literature (Table 2.2). Since the rainfall volume of a single extreme event is more or less equivalent to the monthly rainfall in the GNIP database, it can be assumed that extreme monthly rainfall in the GNIP database was due to one heavy rainfall event. Table 2.2 shows the relation between the Mediterranean origin of extreme events, while no consistent d value could be found for these five events. It should be noted that Tables 2.2 and 2.3 do not take into account the same databases. For the Table 2.2, the 40 events are those extremes cited in the literature (Lopez Bermudez and Romero Diaz, 1993; Poesen and Hooke, 1997). For the Table 2.3 data come from the isotope signatures in precipitation from the Global Network for Isotopes in Precipitation (GNIP), IAEA (2004). This discrepancy explains why extreme events do not generally correspond to Mediterranean isotopic signatures in Gibraltar or Barcelona.

Table 2.2. Extreme events recorded in Spain and Gibraltar compared to the GNIP stations of Barcelona and Gibraltar.

Date	Region	storm ¹	GNIP Station ⁴				Weather conditions ²
			BARCELONA		GIBRALTAR		
		mm	mm	d-value	mm	d-value	Atl/Med
Nov 62	Catalonia	250			157	17.8	—
Oct 73	Murcia	191			117	10.7	Atl
	Andalusia	173-600					
	Balearic Islands	281					
May 77	Valencia	175			37	12.64	—
Oct 77	Catalonia	352			137	20.3	Med
	Valencia	200					
	Andalusia	180-184					
Nov 77	Valencia	377->1000			133	20.06	—
Nov 80	Andalusia	168			121	11.66	—
Oct 82	Catalonia	108			117	14.32	Med
	Valencia	200->600					
	Murcia	160					
Nov 82	Catalonia Andalusia	201-341					Med
Nov 83	Catalonia	237-576			303 ³	8.4	Med
Nov 85	Valencia	259-373	81	14.2	230	0.8	—
Jul 86	Murcia	128-143	28	32.6			Med
Oct 86	Valencia Murcia	>1000 165-270	93	16.9	51	11.94	—
Oct 87	Catalonia	397	331	8.78	125	9.54	—
Nov 87	Valencia Murcia	316-817 304	54	10.3	261	12.82	Med
Sept 88	Valencia	258	104	16.34			—
Oct 88	Andalusia	160	33	10.54	103	11.18	—
Nov 88	Catalonia Murcia	220 120-152	221	16.64	263	10.42	—
Sept 89	Valencia Murcia	242 126-230	61	17.2			Med
Oct 89	Andalusia	202	8	8.6	102	14.9	—

¹ Lopez Bermudez and Romero Diaz, 1993; Poesen and Hooke, 1997; Alonso-Sarria et al. 2002.² Alonso-Sarria et al. 2002. Atl: Atlantic origin ; Med: Mediterranean origin.³ Storms > 0.8 le are marked in bold⁴ Monthly rainfall

Weighted mean d value for the GNIP stations on the Iberian Peninsula were calculated for months with rainfall of over 100 mm and over 150 mm (Table 2.3). For all stations except Faro, it can be observed that more rainy months enrich the weighted mean d values and therefore, it can be assumed that the heavy storms have a Mediterranean origin (Celle-Jeanton et al., 2001a).

Table 2.3. Weighted mean d -value (‰) of precipitation for the western Mediterranean.

GNIP Station	Measurement period	Weighted mean d -value (‰) (number of data)	Weighted mean d -value (‰) Rainfall >100 mm (number of data)	Weighted mean d -value (‰) Rainfall >150 mm (number of data)
PORTALEGRE	1988 - 1999	13.14 (106)	13.61 (29)	13.62 (15)
FARO	1978 - 2001	11.68 (118)	12.00 (25)	11.94 (10)
GIBRALTAR	1961 - 2001	11.95 (188)	12.21 (71)	12.72 (36)
BARCELONA	1985 - 1982	11.76 (70)	13.31 (11)	13.92 (3)
GENOA	1961 - 2001	9.87 (308)	10.37 (111)	10.67 (66)
TUNIS	1968 - 1998	9.64 (178)	12.59 (24)	14.07 (9)

2.3.3 Comparing the isotopic signatures of precipitation, local runoff and groundwater in the

Sierra de Gador-Campo de Dalias aquifer

Long-term records of the isotopic signature in precipitation do not exist for Almeria province (Table 2.1). Precipitation was sampled in the Sierra de Gador for a single event in April 1990 (Cruz-San Julian et al., 1992; Vallejos et al., 1997), events in October 1999 and January 2001 (Vandenschrack et al., 2002) and snow in January 2001 (Vandenschrack, 2002). The mean d value in April 1990 was about 15‰. This value, indicating a western Mediterranean origin, was corroborated by the weather maps during the event (Cruz-San Julian et al., 1992). The agreement between the d value and the origin of the weather systems also holds for the snow (d value=15.8‰) of Mediterranean origin in January 2001 and the local runoff (d value=10.6‰) included three Atlantic storms in October 1999, which was sampled from traditional water harvesting systems (van Wesemael et al., 1998).

Water samples collected from groundwater in the Sierra de Gador by Vandenschrick et al. (2002) are aligned in a δD - $\delta^{18}O$ diagram on a regression line with a slope lower than eight (6.58 with $R^2 = 0.9$). Vandenschrick et al. (2002) interpreted this lower slope gradient as resulting from mixing between precipitation of Atlantic and Mediterranean origin, rather than from evaporation. Deep groundwater within the Campo de Dalias and the Sierra de Gador has a d value ranging from 11.4‰ to 15.1‰, and an average of 13.6‰. The mean d value of shallow groundwater in the Sierra de Gador is on average 12.1‰ (Table 2.4). The latter value is between the d value of the precipitation (10.6‰) and the d value for deep groundwater. These points correspond to percolation of precipitation into local perched water tables in the Sierra de Gador. Vandenschrick et al. (2002) demonstrated that within a karstic aquifer system water with different isotopic signatures can co-exist. The monthly weighted $d_{x_{max}}$ value for the south and east coast of the Iberian peninsula (with $d_{x_{max}}$: 11.81 ± 0.38 ‰) is substantially lower than the d value of the deep groundwater (Fig. 2.2 and Table 2.4). The negative exponential increase of the weighted d_x value with precipitation volume suggests, however, that a better match between d from precipitation and groundwater would be obtained when only extreme events would be considered.

Table 2.4. d values of surface and groundwater samples in the Sierra de Gador and Campo de Dalias.

Site type (number of site)	Sampling ^{1&2}	d -values (‰) $\pm$ Standard Error, minimum, maximum
Runoff in the Sierra de Gador (10)	Two campaigns in 1999 and 2001 ¹	10.6 $\pm$ 0.7; 8.3; 14.8
Shallow groundwater in the Sierra de Gador (5)	Two campaigns in 1999 and 2001 ¹	12.1 $\pm$ 0.4; 11.1; 13.3
Deep groundwater on the fringe of the Sierra de Gador (16)	11 boreholes, one campaign in October 1999 ¹ 5 boreholes sampled monthly from October 1991 to March 1993 ²	13.6 $\pm$ 0.2, 11.4; 15.1

¹ Vandenschrick et al. 2002

² Vallejos et al. 1997

The GNIP stations Faro, Gibraltar, Almeria and Barcelona are closest to the study area, and therefore the most appropriate to analyse the d values of extreme events. Although there are strong differences in annual precipitation between these stations, we have demonstrated consistent trends in d values with rainfall quantity (Fig. 2.2, Table 2.3). This regional character is also reflected in the simultaneous occurrence of the majority of extreme events in large areas along the Mediterranean coast of Spain (Table 2.2).

Faro, Gibraltar and Barcelona have a long record (14 years for Faro, 22 years for Gibraltar and 10 years for Barcelona, Table 2.1). The data for Almeria can, unfortunately, not be considered because of the incomplete record (Tables 2.1 and 2.2, Fig. 2.3). The mean weighted d_s values for Gibraltar, Barcelona and Faro were calculated for rainfall depth intervals starting from the maximum monthly rainfall (eq. 2.4 and Fig. 2.3). The isotopic data from Faro show a typical Atlantic signature, the d_s value always being below 12.5‰ and they are excluded because they cannot be compared to the d value of the deep groundwater (13.6‰). In contrast to the Barcelona data, the Durbin-Watson test showed an autocorrelation for the Gibraltar data, therefore an autoregressive model was used for this station only. The d_s values of Gibraltar and Barcelona increase significantly (the p-values are respectively 0.019 and 10⁻⁵) with precipitation starting from the d value ultimately reached in Fig. 2.2 (Fig. 2.3, Table 2.2). Meanwhile isotopic data for Barcelona show a clear Mediterranean influence compared to those of Gibraltar i.e. higher d_s -values already occur at lower I_e values. Gibraltar shows both an isotopic influence from the Atlantic and the Mediterranean. Due to the location of the study area, it is supposed that its dominating isotopic influence is between those of Barcelona and Gibraltar. The d values of the groundwater in the study area (13.6‰) should be related to a value for the Index of extreme events (I_e) above which the bulk of the recharge would have occurred (Fig 2.3). Such events are characterised by an I_e between 0.7 and 1.4. The large value of I_e (0.7-1.4) indicates the importance of extreme events in recharging the aquifer.

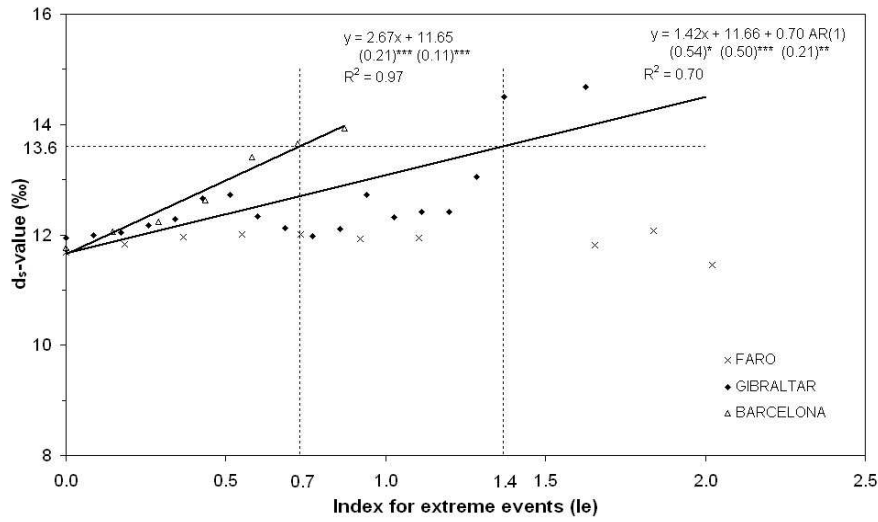


Figure 2.3. Weighted mean ds -value (Eq. 4) versus index for extreme events (I_e) for Faro, Gibraltar and Barcelona. I_e equals rainfall divided by twice the rainfall of the rainiest month (Conte et al, 2002). Events with $I_e > 1$ are considered to be extreme. *,** and ***=significant at 0.05, 0.01 and 0.001 probability levels, respectively. AR(1): first-order autoregressive model. Data extracted from IAEA (2004).

2.3.4 The return period of rainfall producing recharge in the Study area

The meteorological station of La Zarba at 1210 m asl in the middle ranges of the Sierra de Gador is considered to derive an estimation of the return period of the monthly rainfall with an isotopic signature corresponding to the deep groundwater. In order to translate the isotopic signature belonging to events above the threshold for recharge for the much wetter area around Gibraltar to the recharge zone of the aquifer in Almeria province, the rainfall of extreme events is standardised for each station by means of the I_e . A monthly rainfall with an I_e between 0.7 and 1.4 has a return period of 0.9-4.9 years in La Zarba (Fig. 2.4). The volume of the monthly rainfall, corresponding to this return period equals 115 to 216 mm. Months with a rainfall of more than 115 mm are rare in La Zarba, where only 25 of such months have been registered from 1961 to 1995 and only five months with more than 216 mm.

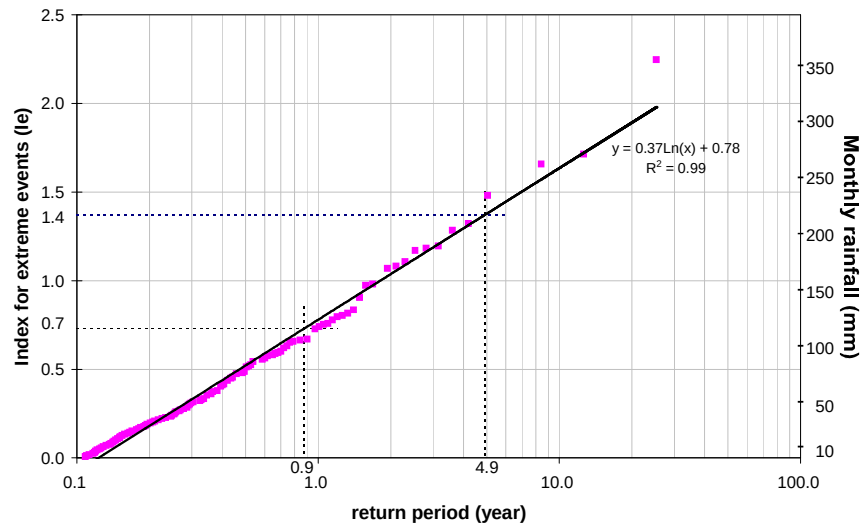


Figure 2.4. Index for extreme events and monthly rainfall versus the return period for the meteorological station of La Zarba.

It is well known that the isotopic signature of groundwater resembles the weighted mean rainfall input (Darling, 2004). In the case of Cheju Island (Korea), Lee et al. (1999) have demonstrated, using the d values from summer and winter rain, that recharge does not occur preferentially in either season. In the case of the study area a different situation occurs since the deep groundwater d values (Table 2.4) are higher than the weighted mean d values from precipitation. Assuming that evapotranspiration in this semiarid region prevents light to moderate rainfall from percolating into the aquifers, we can determine the total rainfall that occurs in extreme events above the $I_e = 0.7$ threshold (Fig. 2.3). Using the La Zarba rainfall data, the recharge is restricted to only a maximum of 37 % of the total rainfall volume for the period 1961 to 1995. Obviously, this is an average for the entire catchment area, and does not preclude that due to the strong altitudinal gradient in precipitation, local recharge forms a more important part of the water balance. Springs draining perched aquifers can react more quickly as demonstrated by their lower d values (12.1‰) following winter rains with an Atlantic signature ($d=10.6‰$; Table 2.4).

2.3.5. Limitations and perspectives

As stated above, the high d values in the groundwater suggest a recharge by heavy rainstorms with a Mediterranean origin (Fig. 2.3, Table 2.3). The most obvious explanation for the absence of an isotopic signal from low and moderate events is the importance of evapotranspiration that would prevent light and moderate rainfall from penetrating below the root zone. However, several limitations can be formulated for this straight isotopic comparison between the present day rainfall and the groundwater in a large and complex aquifer.

The hydrogeology of the Sierra de Gador and Campo de Dalias is complex, and discontinuities are abundant (Fig. 1.1). The Sierra de Gador is a karstic aquifer with two parallel flow systems: a porous aquifer and a system of karstic channels with much higher transmissivity (Vallejos et al., 2003). Water with different isotopic signatures can co-exist and none of these may necessarily reflect the weighted mean isotopic composition of the precipitation. Furthermore, the latter may have changed over time. In which case the isotopic signature of the groundwater would not represent the present day recharge. Molina et al., (2002) observed no seasonal variation in the isotopic signature of groundwater in the Campo de Dalias, which suggests that its residence time is at least several years. An analysis of tritium content and radiocarbon data confirms that the water in the aquifer dates from 1000 to 2000 years (Vallejos et al., 2003). However, taking in account the complexity of the aquifer for which knowledge is still limited, a mixing process with ancient water in the aquifer may mask the presence of recent recharge (Vallejos et al., 2003). A time series analysis, on stable water isotopes using a nested approach at the hillslope scale to sources and finally on groundwater will be an attractive assessment for the understanding of the hydrogeology of the Sierra de Gador – Campo de Dalias. The monitoring was initiated by the Estación Experimental de Zonas Aridas, CSIC (Spain).

It was shown above that a large part of the annual precipitation (c.60%) does not contribute to recharge of the aquifers in the study area. A specific challenge is to increase recharge from events with a low return period, which yield low and intermediate quantities per event, but form the bulk of the annual precipitation. Martin Rosales (2002) calculated the potential for recharge upstream of 107 checkdams within the ephemeral streams on the southern slope of the Sierra de Gador. For an event with a five years return period he estimated a runoff coefficient of 0.24 and an infiltration of 2.4 % of the rainfall upstream of these retention dams. These dams would probably not significantly increase the contribution of moderate rainfall to groundwater recharge, since it is known that in arid and semi arid areas runoff generated by such events does not even reach the ephemeral streams (e.g. Yair and Lavee, 1985; Puigdefabregas et al., 1999). According to Figs. 2.3 and 2.4, a storm with a 0.9-4.9 return period has an isotopic signature similar to that of the deep groundwater, and the potential for recharge of these measures can therefore not be evaluated. Optimizing deep percolation of runoff from moderate events, which currently do not contribute to recharge, could be an alternative. Measures to improve recharge from moderate storms with a return period of under 0.9 year need to target those parts of the hillslopes with high runoff potential such as rock outcrops and shallow soils. Lavee et al. (1997) and van Wesemael et al. (1998) have shown that the efficiency of such techniques depends largely on the surface characteristics of the catchment area, and that generally infiltration losses increase with the catchment area. In analogy with traditional water harvesting techniques, runoff generated on patches of the hillslopes could therefore be concentrated using small dams and channels on the hillslopes. However, the potential of these techniques to generate a significant contribution to recharge needs to be further investigated.

2.4 Conclusions

The analysis of deuterium excess d in precipitation of stations in the GNIP network around the Mediterranean basin allowed us to characterise the origin and type of precipitation in the western Mediterranean. Two main sources of precipitation, the Atlantic Ocean and the western Mediterranean were identified in the literature. For the southern and eastern coast of the Iberian peninsula an exponential increase of d values with precipitation volume was observed. This is in agreement with the Mediterranean origin of extreme events reported in the literature. This relationship could, however, not directly be applied to identify the recharge the large karstic aquifer system of the Sierra de Gador-Campo de Dalias, since the d values in the aquifer exceed those of the weighted mean precipitation, suggesting that light and moderate rainfall does not contribute to recharge. A weighting of d values starting with the extreme events and gradually including more moderate storms provides an estimate of the type of storms dominating recharge and their return period. The infrequent occurrence of these events (return period: 0.9-4.9 years) means that only a maximum of c. 37 % of the total precipitation contributes to recharge. Measures to increase recharge should primarily target deep percolation during moderate rainstorms. Studies focusing on the western Mediterranean are still limited and the conclusions of the chapter on the origin of precipitation on recharge are hardly comparable to other semi-arid region. The results on the type of events (light, moderate or extreme) and the return period, obtained in this chapter need to be compared with other sites in order to strengthen the methodology. Concentration of local runoff on the hillslopes, followed by infiltration below the root zone could be an alternative, which should be investigated further.

Chapter 3

Water harvesting potential in function of hillslope characteristics, a case study from the Sierra de Gador (Almeria province, south-east Spain)²

Outline

Surface water in limestone and dolomite mountain ranges in semi-arid regions is very rare. Therefore, water harvesting systems, collecting the runoff from hillslopes, can be found at regular distances to supply water points for grazing animals. The hydrological behaviour of a range of hillslopes and small catchments can thus be studied by monitoring the rainfall and runoff for such water harvesting systems. The number of runoff events collected in four of such systems ranged from 2 to 22 per year during a seven-year period in the Sierra de Gador (Almería province, Spain). The large variation in runoff response can be attributed to the distribution of the rainfall (long-term average 400 mm) and the characteristics of the catchment areas. Rainfall-runoff behaviour was far more erratic than reported for plot studies and rainfall simulations in other semi-arid regions, demonstrating that plot scale results cannot be extrapolated to design water harvesting systems. The aim of this study was to determine thresholds for the production of runoff on hillslopes and zero order catchments reaching the water harvesting reservoirs at the footslopes. Multiple logistic regressions showed that the rainfall depth per

² This chapter is based on an article by Frot, E., van Wesemael, B., Benet, A. S., House, M. A., 2008. Water harvesting potential in function of hillslope characteristics: A case study from the Sierra de Gador (Almeria province, south-east Spain). *Journal of arid environments* 72 7 1213-1231. 10.1016/j.jaridenv.2007.12.009

event and the antecedent precipitation index over 20 days (API20) are the main parameters to explain the occurrence of runoff in the reservoirs connected to the four catchments. The hillslopes show a systematic pattern of rock outcrops on the crest and shoulders to a colluvial mantle at the footslopes, where the cisterns are dug out. The rainfall and API threshold of the four catchments, required to produce runoff in the reservoirs, are lowest for hillslopes with a short distance from the rock outcrops to the reservoirs and a low vegetation cover. It was demonstrated that i) re-infiltration of runoff frequently occurs (56 events not reaching the reservoirs against 14 events with continuous runoff) even within the unlined channel connecting the cistern to the hillslope, and that ii) the 80 percent probability of runoff occurrence, calculated using the logistic regression, can be used as a proxy for the total annual runoff to be collected.

3.1 Introduction

Water harvesting systems, collecting and storing runoff from impermeable surfaces are still being used in many parts of the world, to resolve water scarcity (see for an overview Tabor, 1995; Lavee et al., 1997; van Wesemael et al., 1998; Schiettecatte et al., 2005; Oweis and Hachum, 2006). These ancient techniques remain a significant source of water for domestics and agricultural purposes. Several authors focus on the advantages to exploit and to provide more effective use of this water conservation technique, such as the potential maximum runoff that could be collected (Senay and Verdin, 2004; Oweis and Hachum, 2006) and the increase of water availability for crops and biomass production (Rockström and Falkenmark, 2000; Fleskens et al., 2005). Since data to validate rainfall runoff models for water harvesting systems are scarce, many systems are built using expert knowledge or oversimplified design criteria. This may lead to an overestimation of the water harvesting potential in particular when the size of the impluvium corresponds to small catchment (e.g. Haregeweyn et al., 2006).

Limestone mountain ranges in the Mediterranean are frequently used for seasonal grazing. Water supply is a major concern, since the karstic nature of the limestones means that surface water is absent and springs are rare and limited to the geological contact with an impermeable lithology. A network of water harvesting systems is thus required to provide the animals with water points throughout the rangeland. Hillslopes draining into concavities would provide ideal sites as an impluvium, whereas cisterns will preferentially be dug out in the colluvial mantle at the foot of the slopes. A network of such systems, locally called aljibes, exists in Almeria province, south-east Spain and a range of sizes of impluvium, connections between the impluvium and the cistern and geomorphological settings (e.g. foot of a near horizontal rocky outcrop, hillslope draining into a channel, first and second order catchment) can be found (van Wesemael et al., 1998). It has been demonstrated that moderate rainstorms, representing the bulk of annual precipitation, do not contribute to

recharge the aquifers in the karstic environment of south-east Spain (Frot et al., 2007). More than 70 % of the annual precipitation is lost by evapotranspiration (Pulido Bosch, 1998; Contreras, 2006). Hence, measures to increase water availability should primarily target either deep percolation or storage of runoff during such moderate events.

Pilgrim et al. (1988) already mentioned the main problems of studying surface hydrology in semi arid and arid regions i.e. collecting data on runoff and the heterogeneity of the soil surfaces leading to discontinuous runoff and vegetation patterns. Although many studies have been carried out since then (see the literature reviews of Puigdefabregas, 2005 and Calvo-Cases, 2003), most studies use small plots or rainfall simulations and thus are not considering scale effects or are focused on individual events. Some studies at the hillslope and catchment scale show that the spatial variability of surface characteristics and hence the hydrological response at the outlet of the catchment are difficult to predict (Bryan and Yair, 1982; Yair and Lavee, 1985; Cerda et al., 1995; Bergkamp et al., 1996 and Puigdefabregas, 2005). This is not surprising since the continuity of runoff pathways through the catchment has been shown to depend on the interaction between a range of factors such as rainfall characteristics (Descheemaeker et al., 2006), soil surface conditions (Abu-Awwad and Shatanawi, 1997; Sole-Benet et al., 1997), stoniness (van Wesemael et al., 2000) and vegetation cover (Puigdefabregas, 2005; Bergkamp et al., 1998). Furthermore, the soil moisture content has been shown to act as threshold for runoff generation (Fitzjohn et al., 1998; Ceballos and Schnabel, 1998; Cammeraat, 2004). In particular when the rainfall intensity is in the same range as the final infiltration capacity, re-infiltration of runoff is likely to occur on parts of the hillslope and the runoff at the outlet of small catchments shows an erratic behaviour (Western et al., 2001).

Water harvesting systems provide ideal sites to study runoff behaviour covering a range of conditions likely to react quickly to rainfall in semi arid landscapes. The hydrological response of these sites can then be used to characterize rainfall-runoff behaviour as a function of the spatial heterogeneity

of soil properties. Based on a seven year data set of rainfall and runoff from four water harvesting systems draining hillslopes and small catchments of different sizes, this study aims to identify the controlling factors and thresholds for runoff occurrence in order to improve the understanding and prediction of surface hydrology and the design of water harvesting systems.

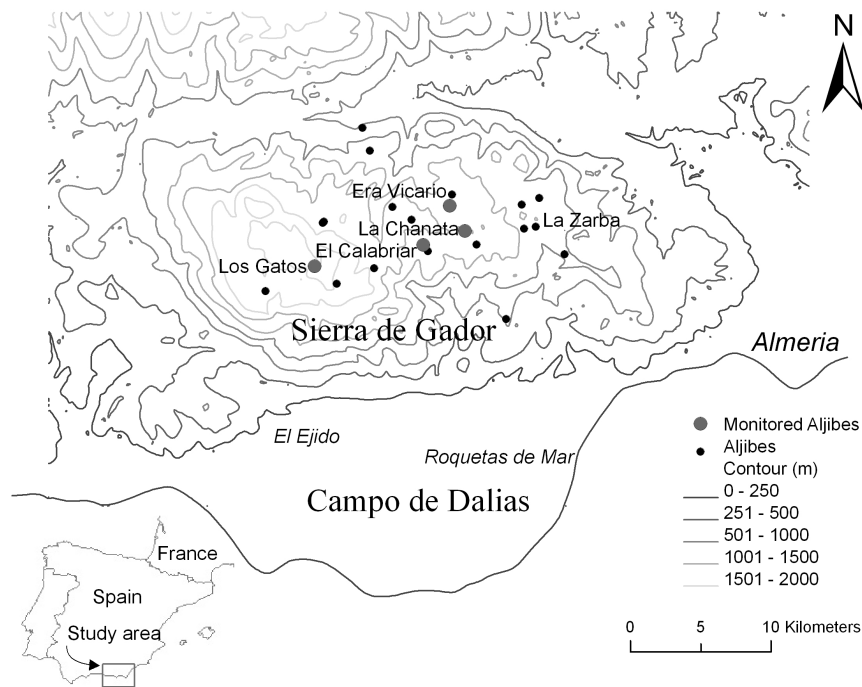


Figure 3.1. Location of the study area (south-east Spain, Almeria province).

3.2 Material and Methods

3.2.1 Selection of the water harvesting systems

Twenty water harvesting systems, locally referred to as aljibes, were found in the Sierra de Gador (Fig. 3.1 and Fig. 3.2). They consist of an impluvium, often a degraded hillslope with a thin and rocky soil or ditches draining dirt roads, a narrow channel to collect the runoff at the bottom of the impluvium and a cistern dug out in the colluvial mantle. The cisterns are covered with a vaulted or concrete roof in order to avoid water loss by

evaporation and preserve the water quality under cool and dark conditions. While most of the aljibes have been abandoned in the more accessible areas of Almeria province with the increased use of groundwater from deep boreholes, the ones in the Sierra de Gador mountain range are still working, and some new ones have been built (van Wesemael et al., 1998).

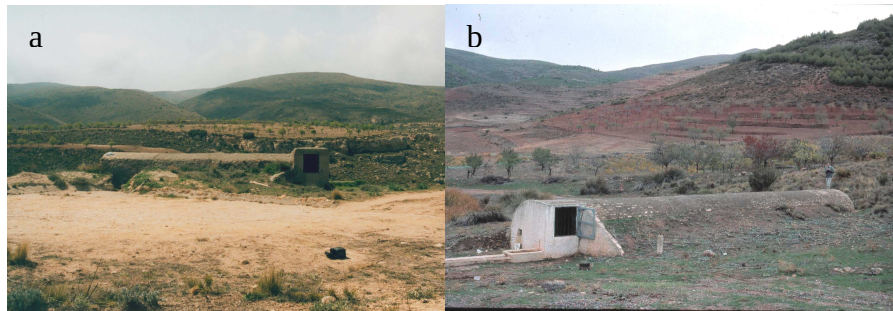


Fig.3.2. Water harvesting systems in the Sierra de Gador: a) Era Vicario, b) El Calabriar.

Four water harvesting systems draining either hillslopes ranging from 0.4 to 6 ha or a small catchment of 21 ha were selected (Fig. 3.2, Table 3.1). Era Vicario is the smallest system (0.4 ha) consisting of a gently dipping impermeable limestone outcrop partly covered by a thin soil. El Calabriar drains a hillslope (2.6 ha) from the rock outcrop at the top to the colluvial mantle at the bottom through a channel at the foot of the slope. The slope is rather steep and some gullies drain into the upslope end of the channel. The geomorphic setting of La Chanata is similar to that of El Calabriar. The channel at the foot of the hillslope is somewhat longer, and therefore the drainage area is larger (6.0 ha). Los Gatos drains a second order catchment with two dry valleys and their hillslopes (21 ha). In general, the distance from the impermeable rock outcrop to the cistern increases with the size of the drainage area (Fig. 3.2 and Table 3.1). The land cover of the four sites can be classified as rangeland with sparse vegetation cover (26-49 %), thin and weakly developed stony soils and a significant fraction of rock outcrops (16-25 %; Table 3.1). The degraded soils on the hillslopes are mainly Rendzic leptosols and the deeper

soils, which were protected from erosion can be classified as Luvic Phaeozems and Calcaric Phaeozems (organic matter: $2.3 \pm 1.3\%$, ICONA-CSIC, 1988 and clay content: 30-50 %, Li et al., 2007 and Moreno, 2005).

The channels, collecting the runoff, are shallow and narrow (< 1 m width) and drain into a sediment trap at the inlet of the aljibe. The capacity of these traps varies according to the design and maintenance of the systems from non-existent in Los Gatos to 0.6 m^3 in Era Vicario, 2.5 m^3 in El Calabriar and 8 m^3 in La Chanata.

Table 3.1. Physical characteristics of the aljibes and their catchments.

Aljibe	Era vicario	El calabriar	La chanata	Los gatos
Altitude (m)	1399	1350	1418	2005
catchment area (m ²)	4,142	26,743	60,021	211,351
Mean Slope (%)	12	35	25	18
Rock outcrop (%)	16	17	25	17
Vegetation cover (%)	26	39	49	46
Vegetation type	herbaceous plants	mattoral shrubs	mattoral shrubs	mattoral shrubs, coniferous species

3.2.2 Hydrological monitoring and characterization of soil surface properties

Tipping bucket rain gauges (ARG100, Environmental Measurements LTD, UK, accuracy ± 0.2 mm) register rainfall depth and intensity at three locations: La Chanata, El Calabriar and Los Gatos. The rainfall of La Chanata at 2km from Era Vicario and at more or less the same elevation was used to characterize the latter site. When data are considered on an event basis, the minimum period separating two events is arbitrarily fixed as one hour. The local meteorological station of La Zarba with records from 1945 to 2000 was used as a long-term reference station (Fig. 3.1 and Table 3.2). For the Los Gatos catchment at 2005 m a.s.l, the altitudinal gradient of 23 mm per 100 meters was applied to adjust the data of the meteorological station of La Zarba before analysing long-term rainfall records (Contreras et al., 2006).

Table 3.2. Annual precipitation statistics for the meteorological station of La Zarba (1219m asl; 1945-2000).

Parameter	Annual
Average (mm)	421.3
Standard error	233.2
Variance	54371.9
Kurstosis	4.3
Minimum	149.0
Percentile ₁₀	219.2
Percentile ₂₅	262.1
Percentile ₅₀	356.3
Percentile ₇₅	500.5
Percentile ₉₀	686.8
Maximum	1288.7
Total	19802.4
Nb	47.0

The runoff is calculated from the volume collected in the cisterns through the hourly recording of the water level using a submersible pressure transducer connected to a data logger (WL14, Global Water inc., US). The accuracy of the probe is 1 cm resulting in an error related to the volume of the aljibe (0.19 m³ for Era Vicario, 0.34 m³ for El Calabriar, 0.61 m³ for la Chanata and 0.82 m³ for Los Gatos). All aljibes have an overflow. In case of overflow, runoff is the sum of the volume stored in the aljibe and the discharge of the overflow. Water loss by partly submerged overflow is calculated by the Cipoletti sharp-crested fully contracted weir equation (eq. 3.1: Ilaco, 1985):

$$q = 1.86 b H^{\frac{3}{2}} \quad 3.1$$

where q is the discharge in m³.s⁻¹, b is the width of the weir (0.4m for Era Vicario, 0.45m for El Calabriar 0.17m for la Chanata), H is the water level in the overflow (in meter). In case of a fully submerged overflow with non submerged orifice equation 3.2 is used (Ilaco, 1985):

$$q = 0.60A\sqrt{2gH} \quad 3.2$$

where A is the cross section m², H is the water level in the overflow (m) and g corresponds to 9.81 m.s⁻².

Since water level is measured in the aljibe, the amount of water required to fill the sediment trap (see section 3.2.1) is not taken into account. The occurrence of runoff in the channel of La Chanata is recorded at two points. The detector consists of two metal strips fixed on a piece of PVC and is connected to a state (i.e. on/off) logger (Hobo State, Onset Inc., US). Only records of more than 5 minutes are considered.

Capacitive soil moisture probes (Theta probe ML2, Delta-T, Cambridge, accuracy $\pm 0.02 \text{ m}^3.\text{m}^{-3}$) were inserted horizontally in the topsoil at 5 cm depth and record the volumetric soil moisture content hourly. Since only two probes were used, one in La Chanata and the other in Los Gatos, the data were used to calibrate a site-specific antecedent precipitation index (API; section 3.2.3).

Spatial variation of soil surface cover was assessed along geo-referenced transects throughout the catchments. At regular interval along transects of different length, 100 observations were carried out on a 1 m^2 surface based on a 10 cm grid, to evaluate the relative proportion of four variables: vegetation, stoniness, rock outcrop and bare soil. A topographical survey of three hillslopes was carried out using a Leica Geosystems Total Station based on a 5 m grid for Era Vicario and a 10 m grid for El Calabriar and La Chanata. Topographical attributes for Los Gatos were derived by digitising 1/10,000 maps with a 10 m contour interval. The digital elevation models were created as follows: each elevation was subtracted from the mean elevation to obtain the map of relative elevation through a spline interpolation using the Arc GIS routine (ESRI Inc., Redlands, USA) at a resolution of 1 m for Era Vicario, 2 m for El Calabriar, 3 m for La Chanata and 10 m for Los Gatos.

3.2.3 Data analysis

Soil surface characteristics

Semi-variograms for the soil surface properties were computed to determine the spatially dependent variance within the catchment. The semi-variogram function allows an evaluation of the semi-variance ($\gamma(h)$) between values for varying distance lags (eq. 3.3):

$$\gamma(h) = 1/2 \text{var}[Z(x_i+h) - Z(x_i)] \quad 3.3$$

Where h is the distance lag between two points and $Z(x_i)$ is the random field value in location x_i . Semivariances, model fitting of the semivariogram and evaluation of the model fit were carried out in Matlab™ (MathWorks, Inc., Boston, USA), using the geostatistical BMElib package (Christakos et al., 2002).

From the modelled semivariogram, a number of parameters describing the spatial structure of the data set can be obtained. The distance at which the modelled semivariance reaches a constant value is termed the range (R) and the corresponding semi-variance value is the sill (C_{tot}). In physical terms, when samples become independent of each other, they are no longer 'related' in a spatial sense. The nugget (C_0) represents the random variation mainly caused by measurement error or sub-grid variability (Cressie, 1991). Finally, the partial sill (C) is the difference between the sill (C_{tot}) and the nugget (C_0). All semi-variogram parameters were estimated by using the best model fit obtained by means of the weighted least square method (Christakos et al., 2002). The ratio between the partial sill and the total variance (C/C_{tot}) describes the part of the variance explained by the spatial model (Cressie, 1991, Guo et al., 2000). The parameters of the semi-variograms were used to interpolate by kriging. After interpolation by kriging, rock outcrop maps were produced using the software package SURFER (Golden Software inc., Colorado, USA).

Antecedent Precipitation Index

The antecedent precipitation index (API) gives an indication of the soil moisture status when direct measurements are not available (Kohler and

Linsley, 1951). This function is a time-weighted depth of previous cumulative rainfall over a given period. API depends on the number of days since the last day with rainfall (n ; eq. 3.4).

$$API_{n(t)} = API_{n-1} + P_{n-1} \cdot k^{\Delta t} \quad 3.4$$

Where n is the number of days considered, Δt is the time (hours) between the start of the rainfall P_n and the end of the last rainfall P_{n-1} (mm) and k is the decay constant. The parameter k describes the soil moisture depletion after rainfall. Heggen (2001) determined the k value as the antilog of the slope in a plot of the logarithm of soil moisture against time. We used the average k for all events for which a clear drying curve could be measured with the capacitive soil moisture probe at 5 cm depth. Many authors reported that the decay coefficient k is a catchment and seasonal parameter (Ancil et al., 2004; Descroix et al., 2002). Two k values were determined in function of the season (k_{winter} , k_{summer}). These k values are obtained for La Chanata and Los Gatos. For the two Aljibes of El Calabrar and Era Vicario the k of La Chanata was applied. The period over which API has to be considered depends on the rate of soil moisture depletion and hence the value of k . Ancil et al., (2002) have tested API time series over 7, 15, 30, 60 and 120 days. Before each rainfall events, API was calculated for 5, 10, 15, 17, 20, 25, 30, 35 days and a non-linear regression model was fitted to the antecedent value of soil moisture contents at 5 cm depth (θ) determined by the theta probe in La Chanata recorded in the study area (eq. 3.5). However the aim of the eq.3.5 was not to model soil moisture but to find the optimal number of days to consider calculating API.

$$\theta = \theta_{\max} - (\theta_{\max} - \theta_{\min}) \times e^{(-bAPI)} \quad 3.5$$

Where fitting variables are $\theta_{\max}$ the maximum soil moisture content, $\theta_{\min}$ the minimum soil moisture content and b is a constant. The performance of the non-linear relationships was assessed by the root mean square error (RMSE; eq. 3.6).

$$RMSE = \sqrt{1/n \sum_{i=1}^n (y_i - \hat{y}_i)^2} \quad 3.6$$

where y_i is the i^{th} observed data and $\hat{y}_i$ is the i^{th} modelled data of n observations.

Effective rainfall duration

The effective rainfall duration (t_{eff} in hours) is defined as the length of the total rainfall event re-evaluated as a function of the percentage of rainfall with intensity larger than 5 mm.h⁻¹ (eq.3.7).

$$t_{\text{eff}} = t_{\text{sup } 5} + (t_{\text{tot}} - t_{\text{sup } 5}) \times \left(1 - \frac{P_{\text{sup } 5}}{P}\right) \quad 3.7$$

where t_{tot} is the total duration (in hours) of the rainfall event, $t_{\text{sup } 5}$ is the duration (in hours) of the rainfall event with an intensity higher than 5 mm.h⁻¹, P is the total amount of rainfall (in mm) and $P_{\text{sup } 5}$ is the amount of rain falling with an intensity higher than 5mm.h⁻¹.

Hence, t_{eff} allows redefining the rainfall duration for which the rainfall is supposed to be more aggressive. Note that the effective rainfall duration of a rainfall event for which the intensity is always lower or always higher than 5mm.h⁻¹ corresponds to the total rainfall duration.

Stepwise logistic Regression

A linear logistic regression was used to calculate the probability of occurrence of inflow into the aljibes (p) using the SAS statistical package (SAS Institute Inc., Cary, NC, USA). This procedure allows the explanatory variables X_n to be used in the prediction of the probability of a binary dependent variable. In our case, the binary variable represents either the occurrence of enough inflow into the aljibe in order to be detected by the water level sensor (accuracy of 1 cm) or no runoff. The logistic model has the form (eq. 3.8):

$$\text{Logit}(p) = \log\left(\frac{p}{1-p}\right) = \alpha + \beta_n X_n \quad 3.8$$

where α is the intercept and β_n are slope parameters and X_n are the independent variables (Dalgaard, 2002).

A stepwise selection of independent variables has been investigated (amount of precipitation (mm), rainfall event duration (in hours), mean intensity I (in mm.h^{-1}), peak intensity during 10 minutes I_{10} (mm.h^{-1}) and 30 minutes I_{30} (mm.h^{-1}), effective duration t_{eff} (in hours) and API20 (mm)). The ability of all fitted models to predict runoff is evaluated from the maximum likelihood estimate and estimated standard error of the parameters, the Wald χ^2 value, the associated probability ($P > \text{Wald } \chi^2$) and the proportional odds ratio. The Goodman–Kruskal Gamma was measured to get the goodness-of-fit which may vary between 0 and 1, with larger values corresponding to stronger associations between the predicted probabilities and observed values (Allison, 1999). The probability values can be expressed by (eq. 3.9):

$$p = \frac{e^{(\alpha + \beta_n X_n)}}{1 + e^{(\alpha + \beta_n X_n)}} \quad 3.9$$

The prediction errors are evaluated by the ‘sensitivity’ which is the conditional probability that case X is correctly classified, $p(X_{\text{alg}} | X_{\text{true}})$ and the ‘positive predictive power’ (PPP) that assesses the probability that a case is X if the algorithm classifies the case as X , $p(X_{\text{true}} | X_{\text{alg}})$ (Fielding and Bell, 1997).

3.3 Results and discussion

3.3.1 Rainfall characteristics

Annual precipitation in La Chanata (1418 m asl) ranged from 270 mm to 675 mm distributed over 64 to 130 events for the period 1999 to 2006 (Table 3.3). Variation in annual rainfall occurs over small distances, since at El Calabrar (1350 m asl at 2.7 km from La Chanata) the annual precipitation

varied from 331 mm to 714 mm for respectively 61 and 137 events. The higher annual precipitation in Los Gatos (2005 m asl) is in agreement with the altitudinal gradient of 23 mm per 100 m (Contreras et al., 2006). However, precipitation in the form of snow is common in some years in Los Gatos. Snow has not been taken into account and this explains the lower precipitation in Los Gatos for 2003 and 2004. The long-term annual precipitation in La Zarba (from 1945 to 2000) ranged from 149 mm to 1289 mm, with an annual mean of 421.3 ± 233.2 mm and a high inter annual variability (Table 3.2). According to the percentile classification, i.e. annual rainfall between the 25th and 75th percentile of the long-term record, the period 1999-2006 is considered as normal (Ramos, 2001; Tables 3.2 and 3.3). The hydrological year 2003-2004 is a wetter than normal year, above the 75th percentile for La Chanata and an extreme year for El Calabriar (above the 90th percentile). The intra-annual variability is marked by a dry season during the summer months (Fig. 3.3) and wetter months occur from October to May. But even during the wettest period the inter annual variability of monthly precipitation is large (Fig. 3.3). The maximum rainfall recorded in one single event was 76 mm for La Chanata, Era Vicario and El Calabriar and 110 mm for Los Gatos. This corresponds to a return period of 23 months.

3.3.2 Soil moisture characteristics

Runoff occurs on average when the soil moisture probes indicate high values in the topsoil i.e. $0.192 \text{ m}^3 \cdot \text{m}^{-3}$ for El Calabriar, $0.303 \text{ m}^3 \cdot \text{m}^{-3}$ for La Chanata and $0.299 \text{ m}^3 \cdot \text{m}^{-3}$ for Los Gatos. This points to the need to quantify soil moisture conditions at the onset of rainfall in order to predict runoff. The soil moisture content follows the seasonal variation of the rainfall with very low values in summer, a general rise in October and quite frequent periods with high soil moisture content from October until May (Fig. 3.4). During the rainy season (October to May) soil moisture depletion occurs over a period of about 30 days for La Chanata and Los Gatos. This refers to the period during which

Table 3.3. Rainfall/runoff events for the period June 1999-October 2006. Rainfall year type is determined by comparison to the long term rainfall record of the local meteorological station of la Zarba (1219m asl.; Table 3.2).

Aljibe		Precipitation				Runoff					
	Year	Total (mm)	Maximum (mm)	nb	Rainfall year type	Total (m³)	Maximum (m³)	Total (mm)	Maximum (mm)	nb	Runoff Coefficient
La Chanata	1999-2000	411.2	76.0	81	normal	47.2	41.9	0.60	0.53	4	0.001
	2000-2001	470.8	68.8	88	normal	173.4	156.1	2.21	1.99	6	0.005
	2001-2002	395.6	45.4	102	normal	9.9	5.5	0.13	0.07	2	0.000
	2002-2003	379.8	57.6	87	normal	19.7	18.0	0.25	0.23	2	0.001
	2003-2004	675.0	42.4	130	wetter	251.6*	232.3	3.21	2.96	3	0.005
	2004-2005	270.0	48.4	64	normal	46.9	28.4	0.60	0.36	4	0.002
	2005-2006	383.2	31.2	100	normal	10.0	7.8	0.13	0.10	2	0.000
Era Vicario						103.8	53.0	28.10	14.35	11	0.068
	same as above					294.1	142.6	79.57	38.59	16	0.169
						68.5	36.6	18.53	9.89	11	0.047
						67.6	55.5	18.28	15.02	11	0.048
						418.4	148.8	113.19	40.25	22	0.168
						181.0	61.9	48.97	16.75	6	0.181
						98.8	53.5	26.74	14.48	4	0.070
El Calabrier	1999-2000	379.2	76.0	76	normal	110.1	100.6	4.38	4.00	3	0.012
	2000-2001	367.0	61.2	80	normal	724.8	600.2	28.82	23.86	6	0.079
	2001-2002	352.2	32.4	92	normal	2.7		0.11		1	0.000
	2002-2003	415.0	57.6	87	normal	130.4	126.3	5.19	5.02	3	0.012
	2003-2004	714.0	56.8	137	extreme	855.9	342.7	34.53	13.62	14	0.048
	2004-2005	331.8	65.8	61	normal	113.2	45.5	4.50	1.81	4	0.014
	2005-2006	353.0	31.2	88	normal	20.8**		0.8		1	0.002
Los Gatos	1999-2000	563.0	110.0	83	normal	18.5	11.0	0.09	0.05	6	0.000
	2000-2001	494.8	63.0	86	normal	9.2	2.8	0.04	0.01	6	0.000
	2001-2002	592.8	55.4	104	normal	17.9	6.4	0.09	0.03	4	0.000
	2002-2003	525.8	51.2	117	normal	12.2	8.7	0.06	0.04	3	0.000
	2003-2004	483.8	37.8	85	normal	7.1	2.1	0.03	0.01	5	0.000
	2004-2005	262.4	59.4	53							

* : incomplete record due to a technical problem for the period of december 2003-september 2004

** : incomplete record due to a technical problem for the period of january 2006-october 2006

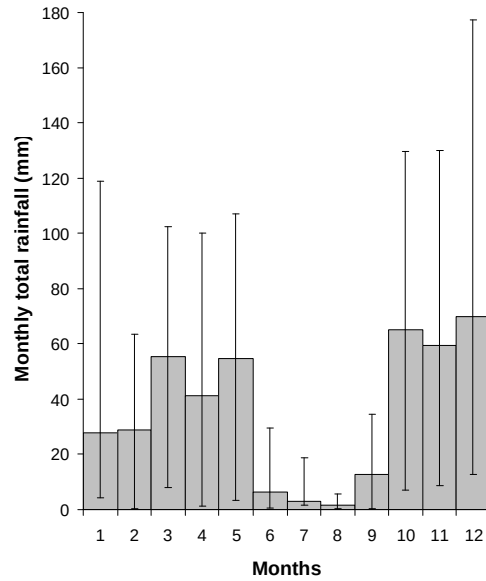


Figure 3.3. Monthly average rainfall for the 7 years record. Error bars indicate minimum and maximum monthly rainfall.

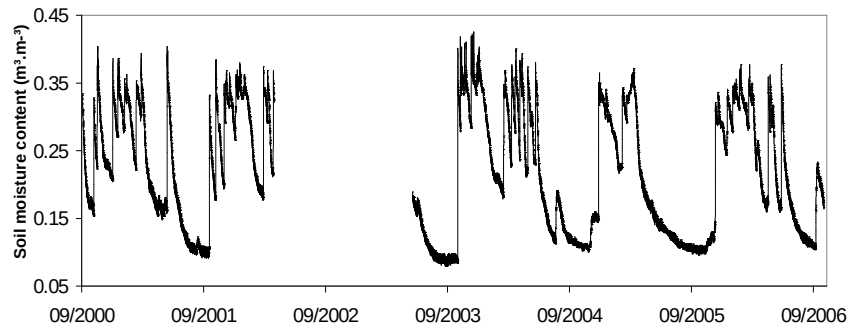


Figure 3.4. Soil moisture contents at 5cm depth for the site of La Chanata (September 2000-September 2006). The lack of data is due to logger problems between April 2002-May 2003.

soil moisture shows an exponential decrease. This period was used to calculate the k of equation 3.4. The k values range from 0.958 (summer in Los Gatos) to 0.973 (winter in La Chanata). These values are rather high compared to the range of k values cited in the literature: 0.80-0.98 (Heggen, 2001). This slow moisture depletion means that even when the rains are sporadic, the soil remains moist for a relatively long period and therefore is likely to produce runoff more quickly. A combination of the low evapotranspiration rates in

winter (22.3 - 30.3 mm per month from October to May; ICONA-CSIC, 1988) and the high water holding capacity of the fine texture soils (clay content = 30% and 50 % according to Li et al., 2007 and Moreno, 2005) is the most likely explanation.

Unfortunately, sites where soil moisture is measured continuously are rare, and this limits the extrapolation of initial soil moisture conditions over time and space. The Antecedent Precipitation Index (API) (Kohler and Linsley, 1951) is often used as an alternative when soil moisture data is not available. API represents the frequency and depth of previous rainfall events with a decay function over time (eq. 3.4). The period over which the antecedent rainfall has to be considered depends on the rate of soil moisture depletion and hence the value of k . Since the k value is relatively high, it can be expected that one has to consider a rather long period for the best prediction of the soil moisture content. We considered a period of 5, 10, 15, 17, 20, 25, 30, 35 days of API as a predictor for the measured soil moisture content (eq. 3.5 and Fig. 3.5). APIs of 5, 10, 15 days were characterized by the highest RMSEs of 0.0714, 0.0631 and 0.0589 $\text{m}^3\cdot\text{m}^{-3}$ respectively (eq. 3.6). APIs of 20, 25, 30 and 35 days produce reasonable estimates of soil moisture content with a best fit for the API over 20 days (API20). RMSEs ranged from 0.0538 $\text{m}^3\cdot\text{m}^{-3}$ for 20 days to 0.0556 $\text{m}^3\cdot\text{m}^{-3}$ for 25 days, 0.0548 $\text{m}^3\cdot\text{m}^{-3}$ for 30 days and 0.0546 $\text{m}^3\cdot\text{m}^{-3}$ for 35 days.

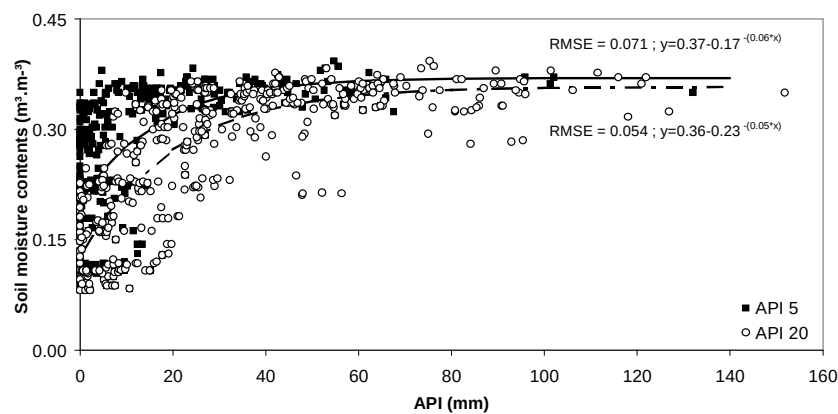


Figure 3.5. Antecedent soil moisture content versus the antecedent precipitation index (eq. 3.4) for 5 days (API5) and 20 days (API20) calculated before each rainfall event.

3.3.3 Runoff

The water level in the aljibes indicates inflow of runoff and depletion of the water by consumption (drinking water for grazing animals) and leakage over a period of seven years (Fig. 3.6). The spikes on the graphs of Era Vicario, El Calabriar and La Chanata indicate that the aljibe fills and overflows for a couple of hours. The overflow is taken into account for the calculation of the runoff volumes (eqs. 3.1 and 3.2). The precipitation seasonality clearly influences the inflow into the cisterns, which occurs from 2 to 14 times per year concentrated in the months from October until May for the larger aljibes (El Calabriar, La Chanata and Los Gatos), and from 4 to 22 times for the smallest aljibe (Era Vicario).

Storms that completely fill the larger aljibes are rare during the seven years i.e. from never in Los Gatos to 3 times for La Chanata and 11 times for El Calabriar. Most aljibes fill up with sharp rises in water level, whereas Los Gatos shows a much more gradual and often stepped response. During winter snow cover has been reported around this aljibe and these gradual flows, sometimes without clear storms, are thought to be due to snowmelt when the tipping bucket rain gauge was frozen and blocked.

Total runoff collected by the aljibes is highly variable from one year to another, i.e. for El Calabriar less than 25 m³ per year in two years and more than 700 m³ in two other years (Table 3.2). Although the amount and frequency of annual runoff follows the same trends as the annual rainfall, it is interesting to remark that the year 2001-2002, which is not the driest, yields the lowest quantity of runoff water during only one event at El Calabriar and two events at La Chanata. The rainfall events in 2001-2002 were apparently rather moderate with the lowest daily maximum (32 mm) recorded at El Calabriar.

There is a clear difference in efficiency between the four aljibes i.e. El Calabriar collected about 1960 m³ in seven years, while Era Vicario collected 1232 m³ and Los Gatos only 65 m³ in five years and saw its water level gradually decrease (Table 3.3 and Fig. 3.6). This efficiency is negatively

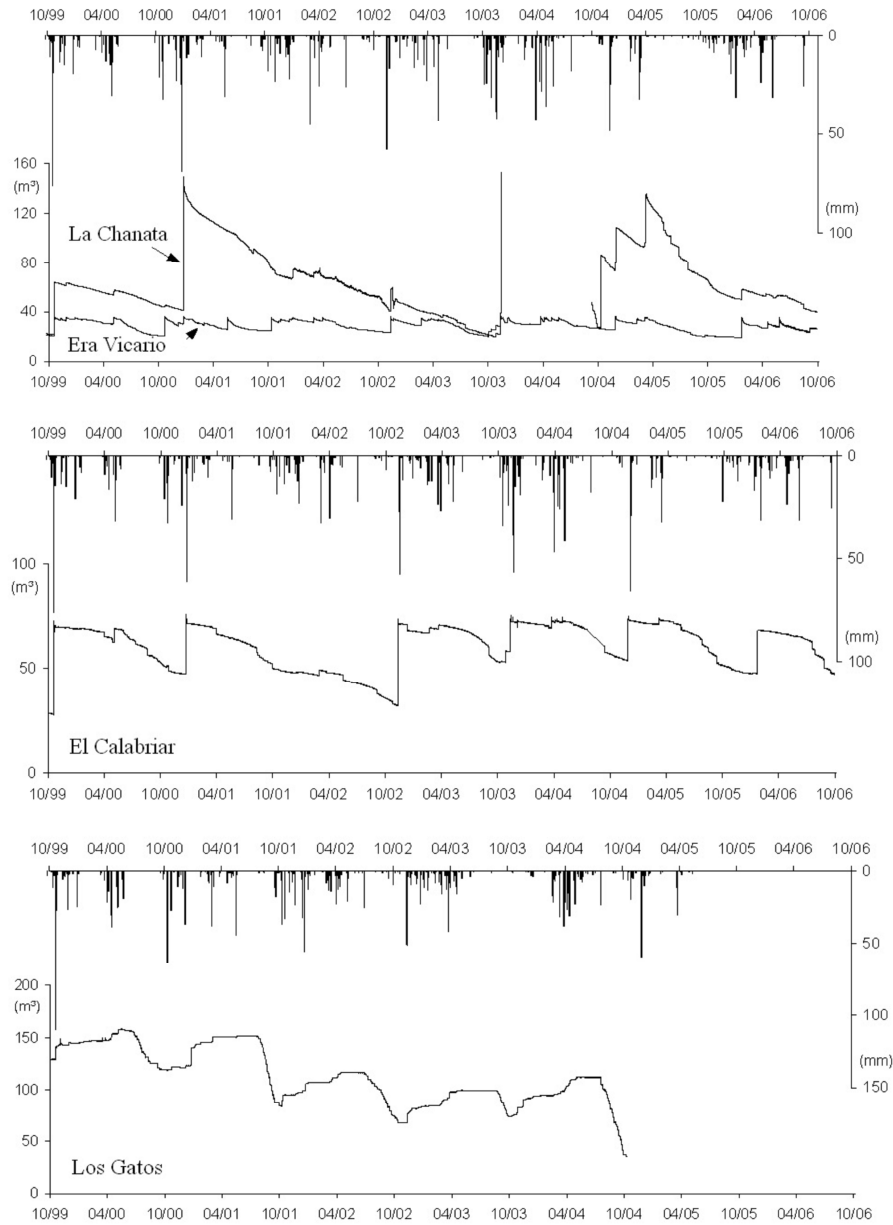


Figure 3.6. Rainfall (right-hand scale) and runoff (left-hand scale) data over the 7 year period.

correlated to the size of the catchment area (Table 3.1). From a first analysis of the rainfall/runoff, it appears that the variability in runoff response is linked firstly to the high rainfall variability and secondly to the size and surface

characteristics of the hillslope. This is clearly illustrated by the behaviour of Era Vicario, the smallest aljibe, with probably the least variation in land cover and the steadiest flow of runoff over the years. We will first discuss the behaviour of the individual aljibes, and then examine whether the spatial arrangement of soil surface characteristics can explain the differences in runoff collection.

3.4.4 Variables influencing runoff

Event variables

As a first approach to understanding the hydrological response of a plot, hillslope or small catchment, runoff is often plotted against rainfall. Although such relationships are far from perfect, a threshold rainfall amount before runoff starts and a slope of the rainfall-runoff curve can often be distinguished (Nicolau et al., 1996; Descheemaeker et al., 2006). Unfortunately, the runoff behaviour for our hillslopes was erratic, and at best some envelopes could be drawn for Era Vicario and El Calabriar (Fig. 3.7). Some events show very high runoff coefficients, whereas most events hardly produce any runoff. The very high runoff coefficients are produced by a sequence of events with an hour or more in between. Given the irregular response of runoff, we decided to concentrate on the occurrence or not of runoff into the aljibe exceeding a volume required to fill the sediment trap and raise the water level by at least 1 cm (the accuracy of the data logger). Given the size of the aljibes, the sediment trap and the impluvium, the detection limit of the runoff corresponds to 0.046 mm for Era Vicario, 0.013 mm for El Calabriar, 0.010 mm for la Chanata and 0.004 mm for Los Gatos. The factors controlling runoff response were analysed by a stepwise logistic regression. In order to carry out the statistical analyses, a dataset was created containing for each event amount of precipitation, rainfall duration, mean intensity, I_{10} , I_{30} , t_{eff} and API20. The stepwise logistic regression revealed only two significant variables and an intercept for three of the four aljibes (El Calabriar, La Chanata and Los Gatos)

explaining runoff into the aljibes i.e. the total rainfall amount and the API20 (Table 3.4). Hence, the probability of runoff into the aljibe increases with rainfall depth and antecedent moisture as estimated by the API20, once a threshold (intercept) has been passed. For Era Vicario, the probability of runoff into the aljibe increases with rainfall depth, antecedent moisture and I_{10} . According to the Wald χ^2 index, the rainfall depth has a higher explanatory power than the API20 for three out of the four aljibes. In contrast, API20 is the most important explanatory variable for Los Gatos. On the one hand, the blocking of the rain gauge in case of snow has probably resulted in an underestimation of precipitation and on the other hand, snowmelt has probably saturated the soil, resulting in a quick response to small events. The significance of the I_{10} for Era Vicario can be explained by the presence of a nearly horizontal outcrop of Tertiary limestone at the entrance of the aljibe. This impervious surface reacts quickly to short outbursts of rain.

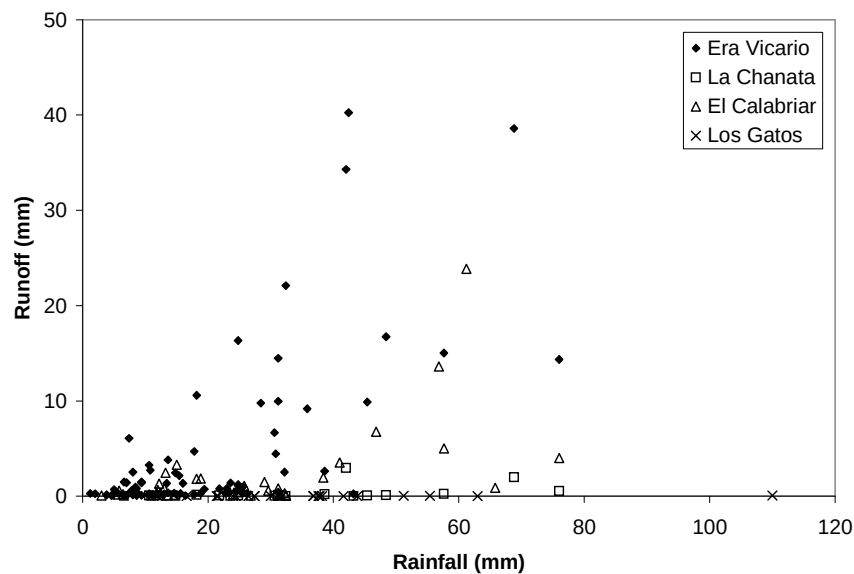


Figure 3.7. Rainfall–runoff curve.

Table 3.4. Analysis of maximum likelihood estimates for the prediction of runoff inflow into the aljibe.

Binary logistic models	Parameter estimate $\pm$ S.E.	Wald χ^2	Pr > χ^2	Odds ratio
<i>Era Vicario (gamma = 0.81)</i>				
Intercept	4.801 $\pm$ 0.809	35.223	< 0.0001	
Rainfall (mm)	0.252 $\pm$ 0.052	23.345	< 0.0001	0.777
I ₁₀ (mm/h)	0.085 $\pm$ 0.042	4.088	0.0432	0.919
API20 (mm)	0.033 $\pm$ 0.009	14.088	0.0002	0.968
<i>El Calabriar (gamma = 0.93)</i>				
Intercept	9.574 $\pm$ 1.853	26.699	< 0.0001	
Rainfall (mm)	0.282 $\pm$ 0.059	22.843	< 0.0001	0.754
API20 (mm)	0.069 $\pm$ 0.015	20.843	< 0.0001	0.933
<i>La Chanata (gamma = 0.90)</i>				
Intercept	7.602 $\pm$ 1.473	26.633	< 0.0001	
Rainfall (mm)	0.226 $\pm$ 0.050	20.419	< 0.0001	0.880
API20 (mm)	0.051 $\pm$ 0.014	14.135	0.0002	0.976
<i>Los Gatos (gamma = 0.87)</i>				
Intercept	6.132 $\pm$ 1.084	31.967	< 0.0001	
Rainfall (mm)	0.161 $\pm$ 0.031	26.315	< 0.0001	0.851
API20 (mm)	0.029 $\pm$ 0.011	6.804	0.0091	0.972

The significance of each parameter is given by the Pr > χ^2 value. The Wald χ^2 value gives the relative weight of each parameter in the model and allows assessment of the role of each explanatory variable in the prediction of runoff.

The logistic regressions can now be used to define the thresholds for runoff into the aljibes for a given probability. For a probability of 0.8, rainfall has been expressed as a function of API20 (Fig. 3.8). This function includes the significant variables for all four aljibes. The intercept value on such a graph represents the minimum rainfall depth required on a dry soil to produce runoff into the aljibe in 8 out of 10 cases. The negative coefficient indicates that the minimum rainfall required to produce runoff decreases as the soil becomes wetter (API20). For dry soils the rainfall threshold is about 24.5 mm for Era Vicario, 38.8 mm for El Calabriar, 39.8 mm for La Chanata and 46.7 mm for Los Gatos (Fig. 3.8).

The performance of the logistic model and the choice of the probability level ($p=0.8$) were evaluated against the following criteria: i) predicting the return period of runoff, ii) sensitivity or in other words: are all runoff events predicted by the model? iii) positive predictive power (PPP) : do all predicted events produce runoff ? (section 3.2.3) and iv) is the runoff volume correctly predicted? During the seven years, runoff at Era Vicario occurred on average nearly once every month (return period of 0.08 y) and for the other catchments about every two months (return period 0.2-0.26 y; Table 3.5). The logistic

model at 0.8 probability underestimates this return period by a factor two (0.16-0.50 y). The model predicted about half of the runoff events (sensitivity, Table 3.5) and nearly all predicted runoff events were also recorded by the water level loggers (PPP, Table 3.5). However, the model predicted all the larger events, representing c. 88 % of the runoff volume for three out of the four aljibes and 59 % of the largest system (Los Gatos). Decreasing the probability threshold will result in a better estimation of the return period and will increase the sensitivity of the model, but will decrease the predictive power of the model. However, the effects will be marginal on the evaluation of the potential of water harvesting as a water resource, i.e. on the runoff volume.

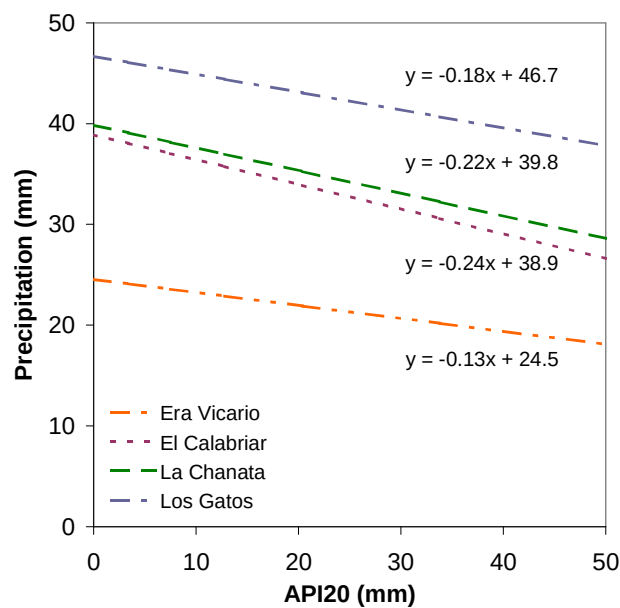


Figure 3.8. The 0.8 probability that runoff occurs is given by the relation between API20 and Precipitation for the four Aljibes of the study area.

Table 3.5. Evaluation of the performance of the logistic model based on a comparison between observed and predicted runoff.

	Return period		Comparison between observed and predicted runoff		
	Observed runoff	Predicted runoff	PPP (%)	Sensitivity (%)	Runoff quantity predicted by the model (%)
Era Vicario	0.08	0.19	97	44	87
El Calabriar	0.20	0.42	100	48	86
La Chanata	0.26	0.45	100	54	88
Los Gatos	0.21	0.50	83	42	59

PPP: Positive predictive power

Hillslope variables

When comparing the hydrological response of the four water harvesting systems, it clearly appears that the threshold required to produce runoff into the aljibe increases with the size of the impluvium (Era Vicario > El Calabriar > La Chanata > Los Gatos; Figs. 3.2, 3.8 and Table 3.1). Only the vegetation cover shows the same trend, where slope gradient and percentage of rock outcrop do not show systematic trends with catchment size (Table 3.1).

Given the ample evidence of the impact of soil surface properties on runoff from semi-arid hillslopes a more detailed analysis of these properties and their spatial pattern is needed. Already in the 1980s, Yair (1983) demonstrated that bare soils and rock outcrop surfaces are known as zones where runoff is generated, whereas vegetation acts as a sink for runoff. Several authors considered the effect of different surface characteristics on soil infiltration. Li et al., (2008) studied the infiltration rates at small catchment scales. They showed that: i) vegetated surfaces have the highest infiltration potential to the extent where a vegetation cover of more than 50% produces no runoff at all, ii) bare soils generate runoff more frequently in particular when they are wet, and iii) the hydrological impact of a rock fragment cover is more complex. The last finding corresponds with the often reported contrasted responses of rock fragments depending on their position of rock fragment on the surface and their size (Poesen et al., 1990; Lavee & Poesen, 1991).

We will now focus on the spatial patterns of vegetation cover and rock outcrop, the two factors that unambiguously influence runoff. The spatial statistics obtained from the semi-variograms and the models used are summarized in Table 3.6. The spatial dependence is highest for vegetation cover and percentage rock outcrop in Era Vicario and for the vegetation cover of Los Gatos (Table 3.6). It should, however, be noted that the percentage of rock outcrop shows a systematic spatial variation for all hillslopes. This corresponds to the interpolation of rock outcrop, field observations and typical sequences on semi-arid hillslopes (Yair, 1983; Poesen et al., 1998) indicating a sequence from rocky slopes on the crest and shoulder to a colluvial mantle on the foot slope (Fig. 3.2 and Fig.3.9). However, for Era Vicario the location of the rock outcrop is different from the other aljibes. This aljibe is built on the edge of a nearly horizontal Tertiary limestone outcrop. Hence, the spatial patterns of rock outcrop refine the explanation for the differences in runoff thresholds between the four systems. The lowest runoff threshold corresponds to the shortest distance between the aljibe or its feeding channel and the area with rock outcrop (Figs. 3.2, 3.8 and 3.9).

Table 3.6. Semi-variogram results for surface characteristics of the aljibes.

Site	Parameter	Model	C ₀	C	R	C/(C ₀ +C)
Era vicario	rock outcrop	spherical	108.2	788.9	8.3	0.88
	vegetation	spherical	24.3	306.6	10.0	0.93
El Calabrar	rock outcrop	linear	406.8	1.4		
	vegetation	pure nugget				
La Chanata	rock outcrop	spherical	306.1	246.6	257.9	0.45
	vegetation	pure nugget				
Los gatos	rock outcrop	linear	99.4	0.9		
	vegetation	exponential	57.4	609.7	16.9	0.91

Co: nugget effect; C: partial sill; R: Range.

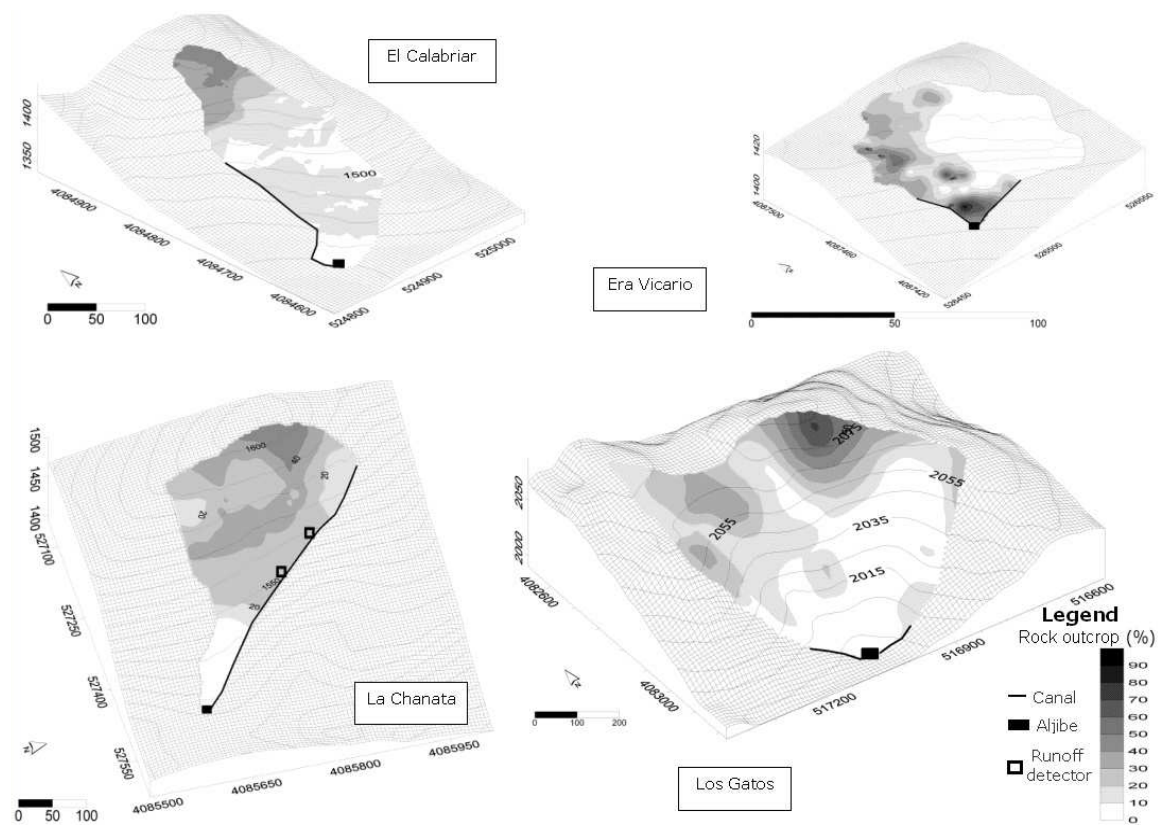


Figure 3.9. The four water harvesting systems, locally referred to as aljibes.

Runoff in semi-arid and arid regions can easily re-infiltrate within the catchment. This explains the decrease of runoff depth (in mm) with increasing catchment area as the main scale effect reported in many studies (Yair and Lavee, 1985; Ceballos and Schnabel, 1998; Cammeraat 2004; Yair and Raz-Yassif, 2004; Li et al., 2008). Within the Sierra de Gador, the storms produced the highest quantity of runoff for the two smallest systems (Era Vicario and El Calabriar) for nearly each year (Table 3.2). Hydrological connectivity is frequently used to describe the transfer of runoff throughout the catchment to the outlet.

Table 3.7. Spatial connectivity for La Chanata catchment corresponding to the mean values of rainfall and API. Runoff inflow between the aljibe and /or runoff detectors (see Fig. 3.2 for their position in the catchment).

<i>Connectivity</i>	<i>Rainfall (±S.E.) (mm)</i>	<i>API20 (±S.E.) (mm)</i>	<i>Nb</i>
0	2.6(3.2)	24.7(19.7)	259
1	6.9(8.4)	18.4(25.5)	56
2			0
3	22.7(12.2)	58.3(39.3)	9
4	42.1(23.8)	50.6(32.2)	5

Connectivity level:

0: no connection

1: Runoff at one or both runoff detectors

2: Runoff at the aljibe only

3: Runoff at aljibe + closest runoff detector

4: Runoff at aljibe + both runoff detectors

The hydrological connectivity can be explained by several factors such as surface depression storage, soil moisture content and infiltration capacity (e.g. Fitzjohn et al., 1998; Western et al., 2001). Connectivity is a dynamic concept, depending on rainfall characteristics and temporal change in soil surface properties. Since linking runoff traces to individual events is difficult and can only be carried out during or just after the event, two runoff detectors were installed in the channel of La Chanata (Fig. 3.9). This allows distinguishing runoff occurring simultaneously in three points along the channel (Table 3.7).

The majority of storms ($n=259$) produce no runoff. On average 7mm of rainfall and API20 of about 18 mm is needed for local runoff in the channel, which does not coincide with runoff into the aljibe. Runoff into the aljibe without local flow in the channel does not occur (level 2 in Table 3.7). This is probably due to the fact that very local runoff at the mouth of the channel is not enough to first fill the sediment trap and then flow into the aljibe. It takes on average 42 mm of rainfall and 51mm of API20 for the runoff to occur simultaneously at both detectors and at the outlet. These observations illustrate that even within an earthen channel where runoff is concentrated, local runoff can re-infiltrate (connectivity level 1). It is obvious that re-infiltration of diffuse runoff in areas with (patchy) vegetation is even more likely to occur.

3.4 Conclusions

Water level monitoring of four water harvesting systems created a substantial dataset on rainfall-runoff relationships in a semi-arid karstic mountain range. The systems collect runoff from hillslopes with varying size (0.3-6 ha) and a small catchment (21 ha) throughout the Sierra de Gador (south-east Spain). Runoff at the outlet was erratic, and therefore we concentrated on the thresholds for runoff occurrence. Runoff into the cistern is explained by two main variables: precipitation depth and soil moisture content as estimated by the antecedent precipitation index (API) and surface characteristics. The concentration of rainfall over the winter season meant that soils dry out quite slowly and that the API had to be calculated over a period of 20 days (API20). A logistic regression produced an 80 % probability of runoff occurrence, this model underestimated the minor events, but at the same time it correctly predicts 59-88 % of the collected runoff volume. The comparison between the four hillslopes reveals that runoff at the outlet is dominated by the spatial patterns of landscape units of low infiltration and the overall vegetation cover. The rock outcrop dominated the crests and the shoulders of the

hillslopes, whereas the cisterns were dug into the colluvial mantle in the footslopes. The hydrological response of the catchment decreased with the distance of the rock outcrop to the channel and the overall vegetation cover. Hydrological connectivity is overall very low, and even the concentrated runoff in the collection channel re-infiltrated for 56 storms, while simultaneous flow at one or two points along the channel and its outlet only occurred for 14 storms. The study shows that potential for water harvesting or artificial recharge can be estimated based on the 80 % probability of runoff occurrence, and that the most suitable sites are close to rock outcrop since re-infiltration of runoff occurs during most events.

Chapter 4

Predicting runoff from semi arid hillslopes as source areas for water harvesting in the Sierra de Gador, southeast Spain³

Outline

The effectiveness of water harvesting systems collecting surface runoff from rangeland hillslopes in semi arid regions is difficult to predict, since the hydrological response at the outlet depends on the heterogeneity of hydrological processes. The lack of continuous runoff pathways, due to the irregular spatial patterns of soil properties and the variety of antecedent soil moisture conditions directly influence runoff generation and control discharge into the water harvesting cisterns. The aim of this chapter is to evaluate the effectiveness of semi-arid hillslopes in generating runoff for water harvesting systems. Runoff was estimated by the STREAM expert-based model which was applied to three semi-arid hillslopes (0.4 to 6 ha). On the one hand the STREAM model rules were adapted to the regional conditions i.e. an antecedent precipitation index was adjusted to local soil moisture conditions and the rainfall duration was defined as the total rainfall event quantity and the effective rainfall duration (P_{tot}/t_{eff}). On the other hand, the distribution of rock outcrop and vegetation cover along the slopes was used to define homogeneous hydrological units. Final infiltration capacities were attributed to these hydrological units based on values found in the literature. The prediction

³ This chapter is based on an article by Frot, E., van Wesemael, B., 2009. Predicting runoff from semi arid hillslopes as source areas for water harvesting in the Sierra de Gador, southeast Spain. *Catena*. 79, 1, 83–92. doi:10.1016/j.catena.2009.06.004.

performances are acceptable for the three water harvesting systems with an RMSE of 13.9 m³. It was shown that the rainfall/runoff model was more sensitive to the duration of the storm than to the antecedent soil moisture conditions. The use of a unique set of hydrological parameters for the three water harvesting systems on representative hillslopes allows the runoff prediction from any rangeland hillslope within the same region. Furthermore, the spatial patterns of soil surface characteristics are crucial for collecting runoff at the outlet of the system. Model runs demonstrated that degradation of vegetation and sealing of very small areas within flow paths can lead in certain conditions to an increase of annual runoff by as much as a factor two.

4.1 Introduction

Water harvesting systems collecting surface runoff are in many parts of semi arid and arid regions the only way to provide water resources for agricultural and domestic uses (Lavee et al., 1991; Oweis and Hachum, 2003; Thomas, 2008). In many cases, traditional systems remain reliable techniques, though their hydrological effectiveness is poorly documented (Senay and Verdin, 2004). Oweis et al. (1999) describe the three components of water harvesting systems such as a runoff producing area, a runoff collection scheme and a runoff storage facility. The runoff production area is described as the main component for the water harvesting effectiveness (Abrisqueta et al., 2007).

At the hillslope scale, the effectiveness of water harvesting systems i.e. the runoff depth at the outlet depends on both runoff generation and runoff transmission. Different approaches and concepts were proposed in the literature to deal with these topics (Calvo-Cases et al., 2003; Puigdefabregas, 2005). In general, Hortonian overland flow is thought to dominate on hillslopes in limestone areas where due to the permeability of the bedrock, the groundwater very rarely reaches the surface. Nevertheless, saturated overland flow as a result of perched groundwater during long rainy spells or a combination of both runoff types have been reported (Yair, 1992; Martinez-Mena et al., 1998; Boix-Fayos et al., 1998). It was generally observed that vegetation cover, type and pattern influence the soil surface characteristics (Bergkamp et al., 1999; Puigdefabregas, 2005). The irregular hydrological pattern with high infiltration rates under the vegetation and low rates in bare areas along the slopes was frequently mentioned to contribute to the hydrological heterogeneity (Boix-Fayos et al., 1998; Puigdefabregas et al., 1999; Calvo-Cases et al., 2003). Bare soils and rock outcrops are considered in most studies as zones where runoff is produced but rapid infiltration under vegetation in many cases disconnects the runoff from the channel (Yair 1992; Bergkamp et al., 1999; Arnau-Rosalen et al., 2008). Given the aforementioned

patterns in infiltration rates, the erratic distribution of rainfall over time, and the large temporal and spatial variation in soil moisture content, further increase the heterogeneity of hydrological properties (Ceballos and Schnabel, 1998; Fitzjohn et al., 1998; Western et al., 1998; Cammeraat, 2004). Hence, the continuity of runoff pathways along hillslopes is often lacking and consequently the hydrological response at the outlet is difficult to predict (Calvo-Cases et al., 2003; Bracken et al., 2005; Croke et al., 2005). It is obvious that distance of runoff producing areas to the main collector can explain the hydrological response at the hillslope and catchment scale (Frot et al., 2008, Arnau-Rosalen et al., 2008).

The optimal location and dimensions of new water harvesting systems requires a more realistic estimate of runoff to be expected. The challenge is to choose a rainfall–runoff model that can accurately predict runoff in the water harvesting system for a given return period of the event. Due to the spatial variability requiring a large number of input variables that are usually not available, the choice of hydrological models was in the past restricted to empirical and lumped ones such as the rational method or the “curve number model” (Soil Conservation Service, 1985). Hence, models have to represent the high disparity of the hydrological response due to the spatial heterogeneity of surface conditions and precipitation characteristics. It appears that models with an aggregated runoff coefficient for the entire catchment are not adapted for semi arid areas (Meerkerk et al., 2009). The use of a decreasing runoff coefficient with increasing surface area as argued by Simanton et al. (1996) and implicitly by Yair and Raz-Yassif (2004) could be a solution when natural hillslopes or catchments are investigated. Moreover, the infrequent rainfall/runoff events, knowledge and available database do not allow considering the use of a dynamic models like LISEM (De Roo et al., 1989; Jetten et al., 1998) or KINEROS (Smith et al., 1995). The latter models increase the input data preparation or could be dependant of other databases for input data not available in situ (e.g. Manning coefficient, leaf area index, soil cohesion and random roughness). Alternatively, expert systems using a global

infiltration/runoff balance for discrete spatial units and a runoff routine towards the outlet have been developed to represent the heterogeneity of the surface conditions and predict event based runoff from agricultural fields (e.g. STREAM, Cerdan et al., 2002 a, b). Two reviews to compare the latter models on different environment were proposed by Nearing et al. (2005) and Jetten and Favis-Mortlock, 2006. The STREAM model has to our knowledge never been applied to rangeland hillslopes in semi arid regions. A previous study showed that for a specific hillslope precipitation depth and antecedent soil moisture were the factors explaining inflow into the water harvesting systems and that distance of impermeable areas to the outlet explained the different behaviour between water harvesting systems. Therefore, an expert system using constant rainfall intensity throughout the event and taking into account the spatial variability of infiltration rates could strike the right balance between model complexity and data availability (Frot et al., 2008).

The objectives of this chapter are to test the potential of an expert based hydrological model to predict runoff generated on semi-arid hillslopes and to evaluate the effectiveness of water harvesting systems to collect runoff. The approach developed and tested in this chapter is based on characterisation of both regional meteorological conditions before and during the storms and spatial heterogeneity of surface properties.

4.2 Material and methods

4.2.1. Model description

The STREAM model is an expert-based approach focusing on the dominant processes resulting in decision rules in the form of matching tables of main parameters. The STREAM model only requires a limited number of input parameters. The model is integrated in a GIS and allows a direct visualisation of the results (Souchère et al., 1998; Cerdan et al., 2002a, b). The model decision rules were initially intended to characterise agricultural fields by an infiltration

capacity for a given rainfall event. For each field, the dominant parameters such as surface crusting state, roughness and vegetation cover were combined into a classification, to which an infiltration capacity was attributed. The initial soil moisture content estimated by the antecedent rainfall within the last 48 hours was used to quantify the initial soil storage (i.e the rainfall depth required to initiate runoff). For each pixel α , a balance between runoff and infiltration ($B\alpha$) can be evaluated (eq. 4.1).

$$B\alpha = P - ST - (I\alpha \times t) \quad 4.1$$

Where P is the rainfall depth (mm); ST the initial soil storage, amount of rainfall needed to reach soil saturation (mm); $I\alpha$ is the steady-state infiltration rate (mm h^{-1}) of the pixel α and t is the rainfall duration (h).

The routing of the runoff is derived from a Digital Elevation Model (DEM) with the possibility to take into account artificial flow lines (i.e. plough lines, ditches, back furrows). For each pixel, the model evaluates the upslope runoff and the runoff generated on the pixel itself.

4.2.2. Model adaptation for the study area

The original model decision rules were evaluated by combining relevant parameters available for croplands catchments in Normandy, France (Cerdan et al., 2002 a, b). Modifications of the model were necessary in order to adapt to the hydrological conditions of rangelands in a semi-arid climate. They resulted in a simplification of the model parameters, structure and decision rules. Hence, a parameterisation phase was required. Input data for the model consisted of (i) a DEM for the determination of the runoff routing (ii) a spatial description of the vegetation and rock outcrop cover defining the hydrological response units (iii) precipitation (depth and duration) and (iv) antecedent precipitation index (API).

Hydrological response units

In order to deal with the spatial heterogeneity of surface conditions, catchments are divided into homogeneous geographical units (Fig. 4.1). The hydrological response for a unit is considered similar regarding runoff generation processes. In the literature, these units were defined as Representative Elementary Area (REA) (Wood et al., 1988), Hydrological Response Units (HRU) (Imeson et al., 1992; Yair, 1992; Cerda et al., 1995; Bergkamp et al., 1996; Cammeraat, et al., 2004) or Morphological Runoff Zones within Hydrologically Similar Surfaces (HYSS) (Kirkby et al., 2005).

The rangeland hillslopes of the water harvesting systems were divided into hydrological response units based on combination of land cover classes (Imeson et al., 1992; Yair, 1992; Cerda et al., 1995; Bergkamp et al., 1996; Bull et al., 2003 and Cammeraat et al., 2004). Attempts have been made to describe hydrological response units through a set of indicators that defined the final infiltration capacities. A characterisation of the main parameters influencing runoff and infiltration in the study area was realised in previous studies (Li et al., 2008 and Frot et al., 2008). These authors show that surface characteristics mainly depend on two controlling parameters: vegetation and rock outcrop cover. The infiltration capacities of hydrological response units are derived from the spatial patterns of these two surface characteristics. Rock outcrop and vegetation maps were obtained by kriging cover percentages that were observed along transects (Frot et al., 2008).

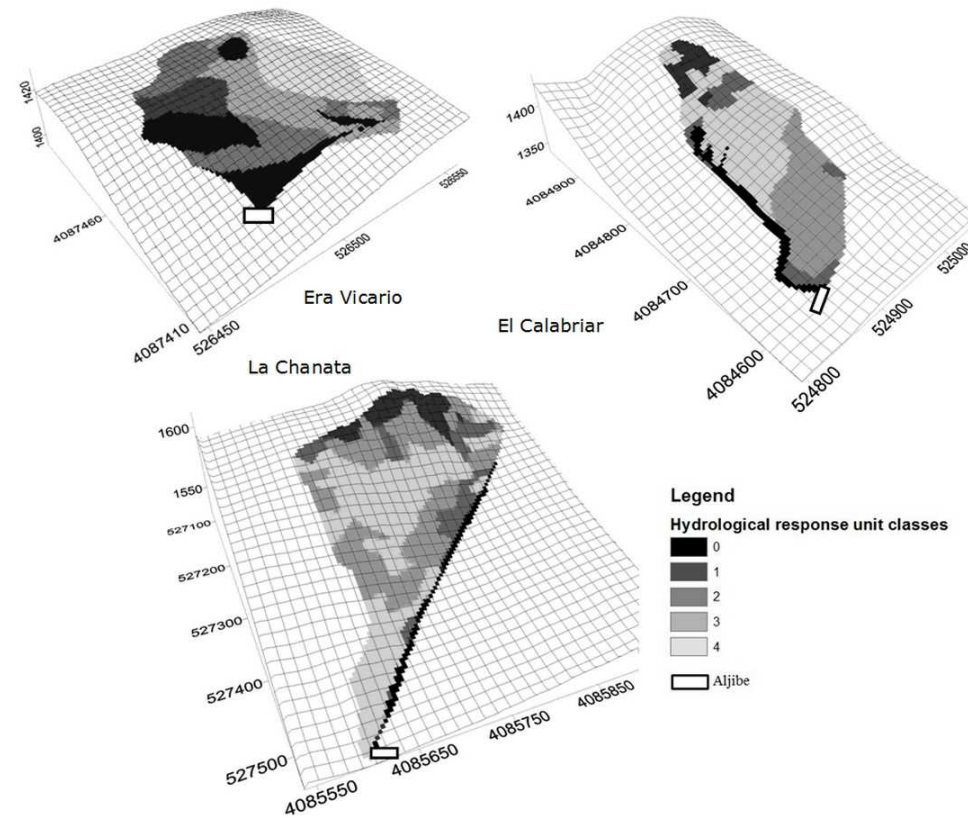


Figure 4.1. Hydrological response units delineated for the three Aljibes (a) Era Vicario, (b) El Calabriar, (c) La Chanata. The hydrological response unit classes are defined in Table 4.2.

Final infiltration capacities

Characterizing infiltration rates is quite problematic in Mediterranean limestone areas. The review of Calvo-Cases et al., (2003) has shown large disparities of final infiltration capacities. Nevertheless, these authors report low runoff coefficients for limestone hillslopes with high infiltration rates under vegetation and the lower ones on areas with rock outcrop. The infiltration rate on bare soils is intermediate and depends on the position and size of rock fragments (Poesen and Lavee, 1994). During rainfall simulations, no runoff occurred on surfaces with more than 50% vegetation cover, 260 mm of rainfall with 55 mm.h⁻¹ rainfall intensity was needed to initiate runoff (Li et al., 2008). These rainfall event characteristics are extremely rare. Bergkamp et al. (1999) have shown that under vegetation the runoff coefficient is close to zero. Final infiltration capacities are adapted from experiments of Li et al. (2008) and literature data (Bergkamp et al., 1999; Calvo-Cases et al., 2003 and Arnau-Rosalen et al., 2008) (Table 4.1). Seasonal variation in infiltration rate, a major feature of the STREAM model for cropland, was not taken into account. The somewhat lower vegetation cover in summer does not have an influence on the runoff, since rainfall is concentrated in the winter season. Neither erosion features, nor soil crusts were observed.

Table 4.1. Final infiltration capacities (mm.h⁻¹) from the literature.

Source	Bare soil (mm.h ⁻¹)	Rock fragments (mm.h ⁻¹)	Vegetation (mm.h ⁻¹)	Rock outcrop (mm.h ⁻¹)	Method
Li et al., 2008	22,5	19,7	187,1	-	Tension infiltrometer
Bergkamp et al., 1999	38,3	-	> 55	-	Rainfall simulation
Arnau-Rosalen et al., 2007	37,7	-	54,1	10	Rainfall simulation

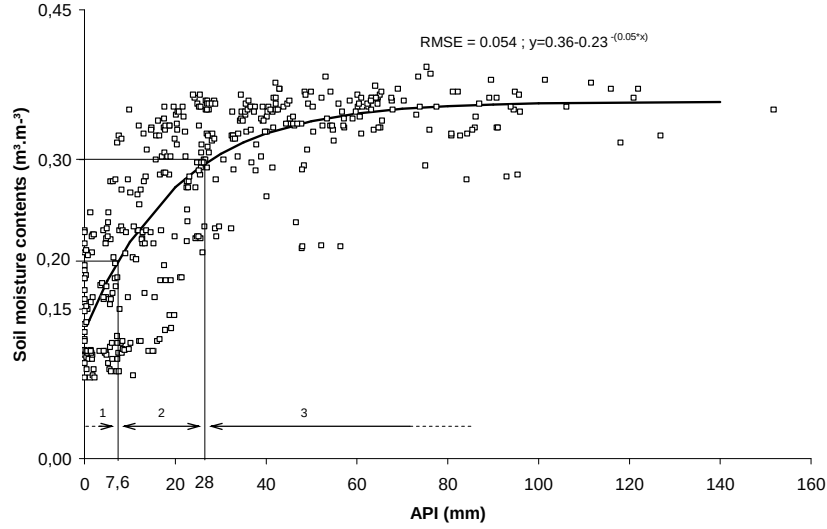


Figure 4.2. Soil moisture content versus API (Antecedent Precipitation Index). Soil moisture states: dry (1); intermediate (2) and wet (3).

Antecedent soil moisture conditions and initial soil storage

A previous study showed that the antecedent precipitation within the last 48 hours was not sufficient to explain the difference in runoff during events with a similar precipitation and therefore the antecedent precipitation index during 20 days (API₂₀) was defined in Chapter 3. The API calculated for 20 days is well correlated to the soil moisture content measured at 5 cm in the soil (RMSE: 0.054 m³.m⁻³; Fig. 4.2). This function is a time-weighted depth of cumulative rainfall over a given period. API depends on the number of days since the last rainfall (eq. 4.2).

$$API_{n(t)} = API_{n-1} + P_{n-1} \cdot k^{\Delta t} \quad 4.2$$

Where n is the number of days considered, Δt is the time (hours) between the start of the rainfall P_n and the end of the last rainfall P_{n-1} (mm) and k is the decay constant. The parameter k describes the soil moisture depletion after rainfall. Two k values were determined in function of the season ($k_{winter} = 0.973$, $k_{summer} = 0.962$; see chapter 3). Finally, three soil moisture content classes were selected: dry (< 0.2 m³.m⁻³; API < 7.6 mm); medium (0.2 - 0.3 m³.m⁻³; API =

7.7-28mm) and wet ($>0.3 \text{ m}^3\cdot\text{m}^{-3}$; $\text{API}>28\text{mm}$) (Fig. 4.2). The ST depends on the land cover characteristics and API and has to be adjusted to the local conditions. For one event, a single API and therefore antecedent soil moisture content was considered for the entire hillslope. The ST was adjusted to take into account the large difference in rainfall depth needed to initiate runoff for the three soil moisture states.

Duration and depth of rainfall

Since STREAM is based on the infiltration/runoff balance (eq. 4.1), the intensity of the rainfall is calculated over the entire event. The variation of rainfall intensity within the event is thus crucial for runoff to occur. Since this parameter is not entered directly in the model, proxies such as rainfall duration and rainfall depth above threshold intensity need to be defined for the region. Several combinations were tested i.e. the total rainfall event depth versus the total event duration ($P_{\text{tot}}/t_{\text{tot}}$), the rainfall depth (mm) and its duration exceeding an intensity of $5 \text{ mm}\cdot\text{h}^{-1}$ (P_5/t_5), and the total rainfall against the effective rainfall duration. The latter was defined as the rainfall event duration re-evaluated as a function of the percentage of rainfall amount with intensity larger than $5 \text{ mm}\cdot\text{h}^{-1}$ ($P_{\text{tot}}/t_{\text{eff}}$, eq. 4.3).

$$t_{\text{eff}} = t_5 + (t_{\text{tot}} - t_5) \times \left(1 - \frac{P_5}{P}\right) \quad 4.3$$

For a storm with intensity always lower or always higher than $5 \text{ mm}\cdot\text{h}^{-1}$, the effective rainfall duration is considered as the total rainfall duration.

Selected events for model adjustment and validation

Model adjustment and validation were conducted on an independent data set covering the same climate conditions for a 7 year period from 1999 to 2006 for the three water harvesting systems. Two sets of events for model adjustment and validation test were randomly selected distributed over rainfall-

API classes proposed in chapter 3 in order to represent the largest possible range of measured conditions. A small number of events were used for the validation. The rainfall/runoff events are quite rare and two thirds have been assigned for calibration and one third for validation.

Some storms were not considered for the adjustment and validation. First, events under the runoff detection limit (0.046mm for Era Vicario, 0.013mm for El Calabriar, and 0.010 mm for La Chanata) were not taken into account. The detection level depends on the size of the aljibes, the sediment trap and the hillslope collecting runoff (Frot et al., 2008). Secondly, events for which overflow occurred and the runoff was suspected to be overestimated are not considered.

Model evaluation

Several statistical indices were used to determine the goodness-of-fit between the total observed and simulated runoff for each event. The coefficient of determination (r^2) describes the goodness of fit of the least square regression. The performance and the accuracy of the estimation of the STREAM model evaluation were assessed by the root mean square error (RMSE; eq. 4.4). The same parameter was used to evaluate the non-linear relationships between soil moisture content and antecedent precipitation index (API).

$$\text{RMSE} = \sqrt{1/n \sum_{i=1}^n (y_i - \hat{y}_i)^2} \quad 4.4$$

where y_i is the observed and $\hat{y}_i$ the modelled value.

The mean error (ME) is a measure for the estimation bias (eq. 4.5)

$$\text{ME} = 1/n \sum_{i=1}^n (y_i - \hat{y}_i) \quad 4.5$$

The average unsigned error (AUE) measures the error proportion in relation with the measured value (eq. 4.6).

$$AUE = 1/n \sum_{i=1}^n 100 \times \left| \frac{y_i - \hat{y}_i}{y_i} \right| \quad 4.6$$

The coefficient of simulation efficiency (Eff) (Nash and Sutcliffe, 1970) evaluates the reliability of prediction (eq. 4.7).

$$Eff = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - y_m)^2} \quad 4.7$$

where y_m is the mean of the observed data of the n observations. An Eff of 1 refers to a perfect prediction of observed data.

Sensitivity analysis

The sensitivity of the model to the two input variables, API and duration of storm, describing the effect of the regional meteorological conditions was tested. Four events were selected according to their return period (T in years) that correspond to a range from light to extreme events for which runoff is likely to occur (i.e. $P=16\text{mm}$ for $T = 0.1$ year ; $P=38\text{mm}$ for $T = 0.25$ year; $P=55\text{mm}$ for $T = 0.5$ year and $P=71\text{mm}$ for $T = 1$ year). The duration and the antecedent soil moisture condition defined by API were tested for each event and revealed several realistic climatic conditions. Three rainfall durations were tested, based on rainfall duration in the study area.

4.3 Results and discussion

4.3.1 Runoff conditions for water harvesting systems

A clear disparity of runoff response was shown between the three aljibes; their effectiveness seems to depend on their land cover and spatial arrangement of units prone to produce runoff (Figs. 4.1 and 4.3; Frot et al., 2008). From the summary statistics, there is a large difference in runoff at the outlet of the three water harvesting system when the soils are dry or wet (Fig. 4.3). Almost, no

runoff occurred under dry conditions (API 1), and very low runoff amounts are obtained in moderate soil moisture state (API 2). For the three aljibes less than 20 % of the rainfall occurred under dry conditions yielding 0 to 1% of the runoff. Precipitation and soil moisture content are directly linked and hence 80% of the storms appeared during moderate to saturated conditions (API2 and API3) corresponding mainly to the winter season. However, around 70% of runoff volume in the aljibes was collected during saturated conditions (API 3; Fig. 4.3). This confirms the importance to consider the antecedent moisture conditions for the prediction of runoff at the outlet.

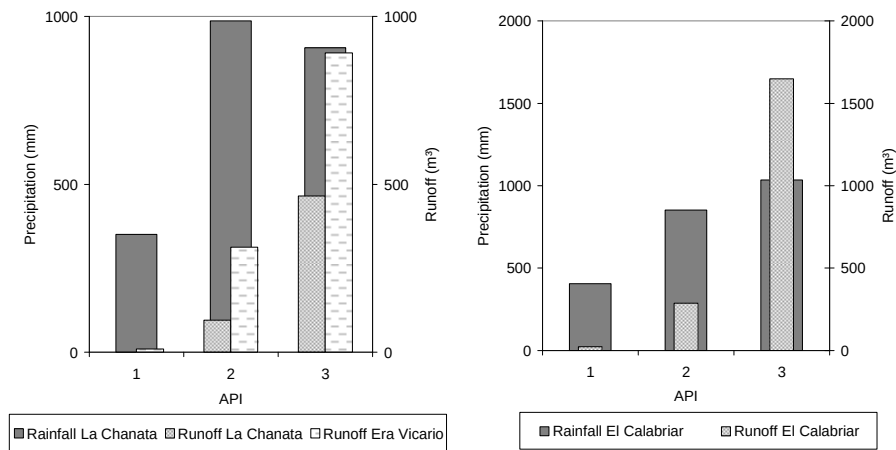


Figure 4.3. Rainfall–runoff events for the period June 1999 to October 2006 classified in function of the API (soil moisture state: dry (1); intermediate (2) and wet (3)).

4.3.2 Model adjustment

In order to describe the hydrological response units, three class intervals of rock outcrop and vegetation cover percentage were used: 0-30%, 30-50% and more than 50% (Table 4.2, Fig. 4.1). These classes are in agreement with the ones proposed by Arnau-Rosalen et al. (2008) : < 25, 25-70 and > 70% with an additional class for bare rock outcrop and litter. The maps of the surface characteristics contain five classes created by the combination of the two land cover maps and therefore five infiltrability classes were defined (Table 4.2, Fig. 4.1). The channel is considered to belong to the class 0. An adjustment of the STREAM model allows changing iteratively the model parameters in order to optimize the agreement between measured and simulated runoff volume. It should be noted that during the iteration parameters were always fixed to a hydrological response unit. Hence, the same parameter values were used for the same class for all three hillslopes. Differences in predicted runoff between the hillslopes for a single storm are thus only caused by differences in the surface area and the spatial pattern of its hydrological response units.

Final infiltration rates for the 5 classes range from 2 mm.h⁻¹ for the rock outcrop and 90 mm.h⁻¹ for the units with a vegetation cover of more than 50% (Tables 4.2 and 4.3). Although, Arnau-Rosalen et al. (2008) attributed a higher infiltration rate (10 mm.h⁻¹) for limestone outcrops as a result of percolation into cracks, this higher infiltrability still produced a lower runoff coefficient than those found in the study area (Frot et al., 2008). The same is true for the study by Cammeraat and Imeson (1999).

The ST which represents rainfall depth needed to initiate runoff for the three soil moisture states is given in Table 4.2. The ST had high values (100 mm) during dry periods especially in vegetated zones where hardly any runoff occurs. Li et al. (2008) have shown that during a rainfall experiment with 55 mm.h⁻¹ rainfall intensity, 260 mm of rainfall was needed to initiate runoff. In contrast, runoff events are more frequent for saturated soils. Under such conditions, the ST was set at 0 mm.

Table 4.2. Hydrological Response Units defined according to rock outcrop and vegetation cover with the corresponding final infiltration capacity and initial soil storage (API described in Fig 4.2).

Classes	Rock outcrop cover (%)	Vegetation cover (%)	Infiltrability (mm/h)	Initial Soil Storage (mm)		
				API 1 ^a	API 2 ^b	API 3 ^c
0	> 50	0-30	2	6	3	0
1	30-50	0-30	6.5	15	8	0
2	0-30	0-30	12	40	18	0
3	0-30	30-50	40	60	40	0
4	0-30	> 50	90	100	60	1

^aAPI 1 : API < 7.6 mm

^bAPI 2 : API = 7.7 to 28 mm

^cAPI 3 : API > 28.1 mm

Cerdan et al. (2001) observed that the STREAM model is sensitive to the rainfall duration. In the semi-arid context, the duration of the rainfall event needs to be clearly evaluated. One of the problems of using a simple rainfall/runoff model is that such a model cannot take the variation in rainfall intensity into account within an event. The selected events were randomly distributed over four classes according to the rainfall-API thresholds for runoff generation (Frot et al., 2008). A large deviation of simulated runoff (m^3) was found when $P_{\text{tot}}/t_{\text{tot}}$ was applied (Table 4.3). Therefore, three rainfall/duration combinations were tested on selected events (Table 4.3). Taking into account the rainfall higher than 5 mm.h^{-1} (P_5/t_5) improves the results. The best fit is obtained when the total rainfall depth and the effective rainfall duration are considered ($P_{\text{tot}}/t_{\text{eff}}$; eq. (3)). The use of t_{eff} for the rainfall duration allows reducing the influence of periods of low intensity on the overall runoff production within an event. t_{eff} allows redefining the rainfall duration for which the rainfall is supposed to be more aggressive.

Table 4.3. Selection of best model parameters reflecting rainfall duration and quantity.

		$P_{tot}T_{tot}$	P_5T_5	$P_{tot}t_{eff}$
Era vicario	ME (m ³)	8,7	5,6	4,0
	RMSE (m ³)	14,9	11,8	10,5
	<i>Eff</i>	-1,2	-0,4	-0,1
Calabriar	ME (m ³)	9,6	5,6	0,3
	RMSE (m ³)	15,4	13,4	12,0
	<i>Eff</i>	0,8	0,8	0,9
Chanata	ME (m ³)	5,4	0,6	0,4
	RMSE (m ³)	7,3	3,0	6,9
	<i>Eff</i>	-0,8	0,7	0,4

4.3.3 Model sensitivity

For a single API class, simulations are run with the three t_{eff} classes and vice versa for four storms (Fig. 4.4) and for three durations. The mean duration of around 5 hours, events with duration of the mean plus one standard deviation (8.5 hours) and events minus one standard deviation (1.4 hours) were considered. Runoff depth was simulated for the combinations of three classes of both API and rainfall duration. The model sensitivity is evaluated based on the maximum difference found in runoff volume for a single storm under two conditions i) t_{eff} is constant and API varies from dry to wet soil moisture conditions and ii) API is constant and t_{eff} ranges from short ($t_{eff} = 1.4$ hours) to long storms ($t_{eff} = 8.5$ hours; Fig. 4.4). Note that the maximum runoff discrepancy occurs on saturated soils (API = 3) and for short storms ($t_{eff} = 1.4$ hours). For the four rainfall depths, changes in t_{eff} produced a larger variation in runoff volume than changes in API class (Fig. 4.4). In particular, during extreme events ($P=71$ mm) a difference of about 300m³ for El Calabriar can be observed depending on the duration of the event. This is the result of two simulations obtained for a same storm of $T=1$ year (71 mm) under the same API conditions (saturated conditions) with a t_{eff} of 1.4 and 8.5 hours. The results confirm the sensitivity of the model to variation in rainfall duration.

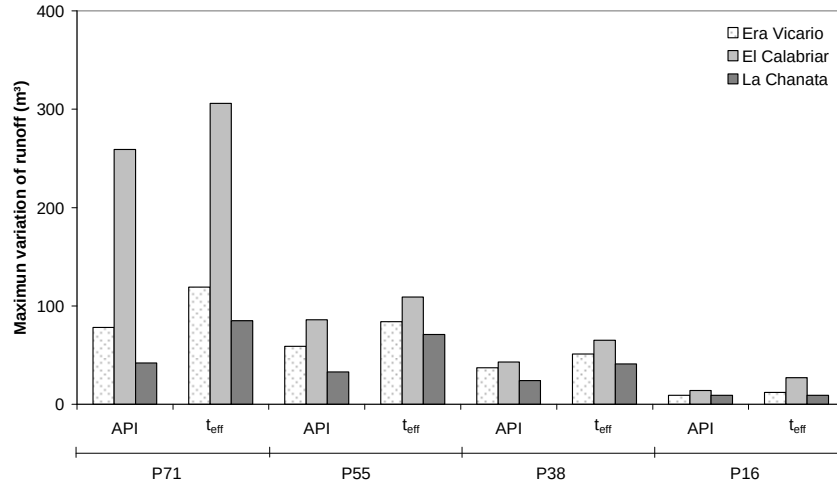


Figure 4.4. Variation of input parameters (API, t_{eff}) for four storms (71, 55, 38, and 16 mm with respectively a return period $T = 1, 0.75, 0.5, 0.1$ years). Values represent the difference in runoff volume for a single storms when i) for API: t_{eff} is constant and API ranges from dry (API 1) to humid (API 3) and ii) for t_{eff} : API is constant and t_{eff} ranges from short ($t_{eff} = 1.4$ hours) to long storms ($t_{eff} = 8.5$ hours). For one storm, only the maximum values of difference in runoff volume are shown.

4.3.4 Evaluation of the model performance

The prediction performances are reasonable for two of the three water harvesting systems (Table 4.4). Considering Era Vicario and La Chanata hillslopes, the modelling results are satisfactory ($Eff = 0.5$). Runoff volumes are correctly predicted ($r^2 > 0.8$ for La Chanata) and reasonably predicted for Era Vicario and El Calabriar ($r^2 = 0.5$; Fig. 4.5 and Table 4.4). The accuracy given by the root mean square error (RMSE) for the three systems is 13.9 m^3 at the outlet (maximum runoff volume was around 150 m^3 in a single event). The accuracy corresponds to about 20% of the yearly average of runoff volume. Given the large variability in annual runoff observed ranging from 0 to 172 m^3 and the low number of events per year, these uncertainties are acceptable for the estimation of the effectiveness of water harvesting systems. On the whole runoff is overestimated ($AUE = 201\%$). For La Chanata, low runoff events are clearly underestimated by the model. Meanwhile, the moderate to high runoff

events tend to be overestimated. Overall, simulated total runoff volume is 129 m³, which is 40 m³ more than the observed measurements and the model prediction on this hillslope is better than the two other study areas. El Calabriar presents the lowest prediction performance ($Eff=0$) and the runoff is largely overestimated ($AUE=182.5\%$). An Eff close to zero suggests that predicted value is as good as the mean value. In case of Era Vicario, the standard deviation (9.7 m³) of the simulated runoff is equivalent to the RMSE and therefore the prediction performance is low.

Four groups are clearly identified on the simulation results. The first group corresponds generally to light rainfall events with dry antecedent soil moisture condition (API1 or API2) for which the runoff volume at the outlet is quite low. These rainfall/runoff events are of little interest for the model results, these events are not real influence on the effectiveness of the water harvesting system. The second group is overestimated simulated runoff volumes. Runoff events of less than 10 mm are slightly overestimated by the model for the three water harvesting systems. They are mainly events in wet (API3) conditions that it may be not representing the real field conditions. For el Calabriar, some overestimated results are explained by inaccurate measurement could be due to non consideration of human influences (e.g. redirection of runoff from the channel). The third group are underestimated simulated runoffs. The underestimated predicted results (Fig. 4.5) correspond to intense rainfall events, in humid conditions (API3) for El Calabriar and in dry condition (API1) for the rainfall/runoff event of Era Vicario. The simulation errors appear to be linked to rainfall duration and probably to an inaccurate evaluation of soil moisture conditions for Era Vicario. Indeed, rainfall events are long (4 to 12 hours) with short periods of rainfall intensity higher than 5 mm.h⁻¹. Variation of rainfall intensity during events is not taking into account by the model. However, the use of t_{eff} (eq.3) improves significantly the predicted results; however it is not enough for some intense rainfall events. Furthermore, a better estimation of antecedent soil moisture conditions would

certainly enhance modelling results. The group four is more or less correctly predicted.

Predicted results are acceptable to assess runoff rates when considering infrequent events and the use of a single parameter set for each catchment.

Table 4.4. Validation results. Evaluation of uncertainty analysis.

	Era Vicario	El Calabriar	La Chanata	Total
n	47	10	11	68
r^2	0.5	0.5	0.8	0.5
ME	1.4	13.0	-3.5	2.3
RMSE	8.3	28.7	12.2	13.9
AUE	212.3	182.5	169.2	200.9
Eff	0.2	0.0	0.7	0.3

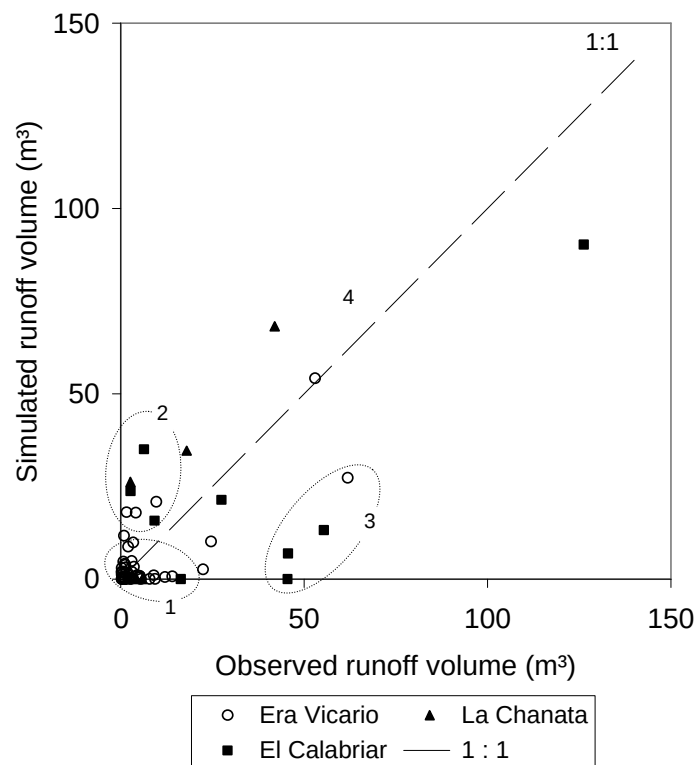


Figure 4.5. Stream model results. Simulated runoff volume versus observed runoff volume for the three water harvesting systems. Four groups of predicted runoff volumes were clustered.

The model was adjusted using a consistent attribution of parameter values to the hydrological response units throughout the three hillslopes of different size. The ability of the model to replicate spatial transmission losses of runoff along semi-arid hillslopes reported among others by Simanton et al. (1996) and Yair and Raz Yassif (2004) is reassuring. Similar patterns were observed to the ones reported by Yair and Raz Yassif (2004) (Figs. 4.1 and 4.6). No runoff was observed where units are dominated by vegetation. Runoff was mainly generated on the upper part of the slope where rock outcrop dominates the landscape. This effect can clearly be seen for the aljibe of Era Vicario with a nearly horizontally layered limestone outcrop at the outlet (Figs. 4.1 and 4.6). For the aljibe of la Chanata, the connectivity was very low; since runoff was mainly produced on rock outcrop units far from the outlet. These units were not directly linked with the channel since some units with denser vegetation were located along runoff pathways and allowed infiltration. In agreement with the study of Arnau-Rosalen et al. (2008), the majority of the catchment does not produce runoff. Runoff only produced in the channel itself never produces a large enough volume to fill the reservoir. As observed for the aljibe of La Chanata by means of runoff detectors in the channel (Frot et al., 2008), the model predicted the connectivity in the channel itself to explain runoff at the aljibe outlet. In other words, no runoff can be detected exclusively at the aljibe entrance without a continuous flow in the channel. The connection between the channel and units of low infiltration rates such as rock outcrops units was restricted to particular API/P conditions (i.e. $T \geq 0.25$ years and a t_{eff} lower than 8.5 hours). For El Calabriar, runoff is mainly produced into well-developed gullies with a low infiltration capacity. Model simulations show a very low connectivity between rock outcrops units and the gullies due to intercalated vegetated units.

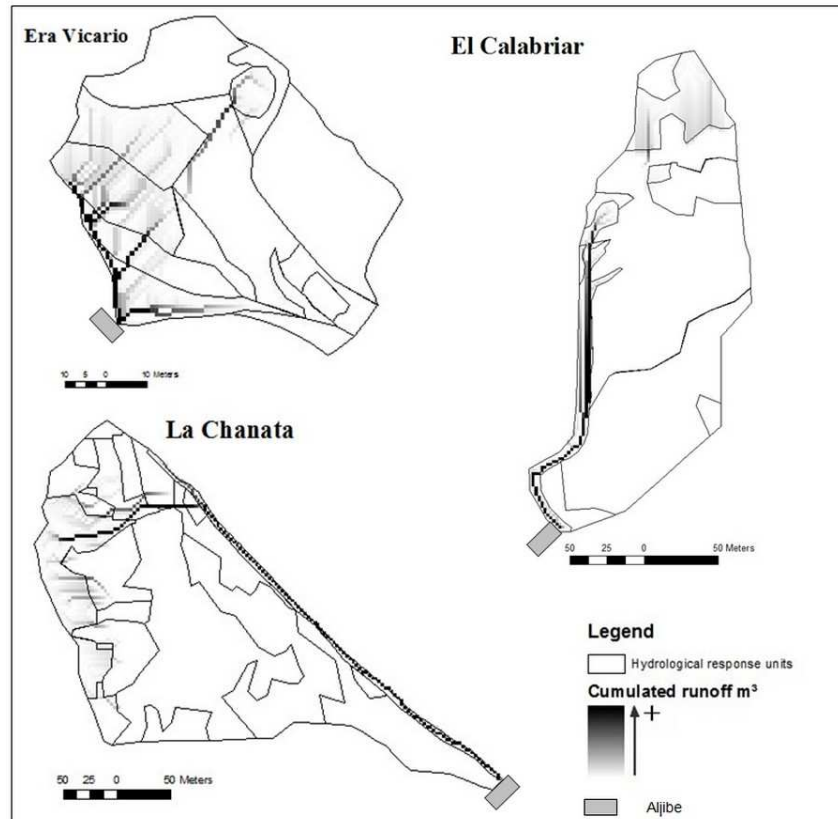


Figure 4.6. Example of simulated runoff patterns for the three water harvesting systems. Simulated runoff was obtained for a rainfall event with $P=55$ mm ($T = 0.75$ year); $t_{eff} = 5$ h, $API = 3$.

4.3.5 Modelling limitation

Adjustment of the STREAM model to a semi-arid environment is quite problematic. This is further complicated by limited data availability required to run independent adjustment and validation runs, and the large spatial variation in final infiltration rates. Two types of adjustments were necessary: i) the expression of the parameters was changed in the case of ST or event duration and ii) the values for parameters such as final infiltration rate for each hydrological response unit had to be attributed. However, the reliability of results could be improved by considering a minimum and maximum infiltration and initial soil storage rates and by testing the sensitivity of model results on

these parameters. A better characterization of input parameters obtained by a field measurement or by using the pedotranfer function will improve model results. Evrard et al., (2009) demonstrated that the STREAM model could be applied within temperate region by only adjusting the final infiltration rates. However, when they tried to apply the model to a Mediterranean catchment without changing the structure of the parameters, the results were unsatisfactory. The experience of Evrard et al., (2009) and our own application in a semi-arid region suggest that the model can be applied within a climate zone, but has to be adapted decision rules or pedotransfer functions would be required before using it outside of this context. Further validation in other climate zones would strengthen this hypothesis.

Several authors considered rainfall intensity as an important factor to explain runoff depth (Reaney et al., 2007; Meerkerk et al., 2009). In our case, the peak rainfall intensity, expressed as the maximum intensity in a 10 or 30 minute interval, was not significant in explaining the runoff reaching the aljibes (Frot et al., 2008). However, the intensity variation during rainfall events probably influenced the runoff production and the connectivity (Kirby et al., 2005). Two events can have the same amount and duration but the sequence of high intensity outbursts can be different and can probably produce diverse responses. This is not taken into account by the model. Constant rainfall intensity during the event was used in the STREAM model. Refining the definition of the duration influenced the constant rainfall intensity and allowed a better estimation of the total discharge at the outlet. In the STREAM model, the spatial heterogeneity of final infiltration rates is taken into account for the runoff generation and connectivity but not for the runoff transmission. Discontinuity of runoff flow velocities can be estimated from the slope gradients and can enhance or reduce runoff transmission losses.

Table 4.5. Aljibe effectiveness based on simulated runoff. Comparison between total runoff (m³) of two hydrological years (wettest and driest over the seven year record period) and the possibility to fill in the *aljibes*.

Aljibe	Runoff volume		Effectiveness ^a		
	wet year ^b (m ³)	dry year ^c (m ³)	wet year	dry year	mean (7 years)
Era Vicario	69.6	38.3	1.8	1.0	1.1
El Calabriar	171.7	41.7	2.4	0.6	1.7
La Chanata	90.4	0.0	0.6	0.0	0.3

^a *Aljibe effectiveness is defined as recharge frequency, i.e. an effectiveness of 1 corresponds to the aljibe filling up once a year.*

^b *The wet hydrological year corresponds to precipitation of 675 mm for la Chanata and Era Vicario and 714 mm for El Calabriar.*

^c *The dry hydrological year corresponds to precipitation of 270 mm for la Chanata and Era Vicario and 382 mm for El Calabriar.*

4.3.6 Water harvesting effectiveness

In semi-arid and arid areas, runoff depth (mm) decreases with increasing catchment area (Yair and Lavee, 1985; Ceballos and Schnabel, 1998; Cammeraat, 2004; Yair and Raz-Yassif, 2004; Li et al., 2006) and generally runoff volume (m³) increases in function of the drainage area (Cammeraat, 2004; Li et al., 2006). This suggests that average runoff parameters for the entire catchment area do not adequately reproduce the runoff depth at the outlet. Two contrasting years on the seven year recording period (270 mm and 675 mm for la Chanata and Era Vicario and 382 mm and 714 mm for El Calabriar) were used to demonstrate the runoff volume (m³) and the effectiveness of the three aljibes defined as the number of times they can be filled (Table 4.5). The aljibes filled only 0.3 to 1.7 times per year with a maximum for El Calabriar of 2.4 times for a wetter hydrological year compared to the one to ten times per year estimated by using the curve number technique (van Wesemael et al., 1998). The evaluation of the effectiveness of a water harvesting system must consider the amount and timing of the water

requirement, and the spatial variability of climatic and topographic parameters. The systems in the Sierra de Gador are along a transhumance route, and provide water to grazing sheep and goat during the summer season. Given the lack of rainfall during the summer, the systems need to be full before the summer and are not replenished until autumn or winter. These criteria are met by the two smaller systems (Era Vicario and El Calabriar; Table 4.5). However, the effectiveness of La Chanata is quite poor (fills up 0-0.6 times per year). This is true nowadays, the pastoral system has been gradually abandoned. At the time when the sheep were more abundant, the pastures were better maintained and the effectiveness of the water harvesting systems should be better. This highlights the importance of the landuse change on the impact on runoff.

The STREAM model provides the hydrological network and evaluates the runoff connections in function of the antecedent moisture conditions, rainfall characteristics and hydrological response units. Therefore, land cover distributions can be rapidly adapted to simulate conditions with a higher degree of connectivity and test the influence on water harvesting system effectiveness. Different scenarios of land cover can be tested and can be helpful to select the best water management options. For example, when the infiltration rates decrease in an area between the main runoff generating area (usually the rock outcrop on the crest and the shoulders of the hillslope) and the channel, the runoff from the rock outcrop will easily reach the outlet (Fig. 4.1 and 4.6). It can be seen that changing the infiltration characteristics of a very limited area within the concentrated flow zone has a large impact on the overall runoff and that in the aforementioned example runoff volume doubles over a single event. The same is true for the total runoff calculated over a seven year period (Fig. 4.7). Hence, either by vegetation degradation due to more intensive grazing or by deliberately removing the vegetation and sealing the surface along the major flow lines, the effectiveness of the water harvesting systems can be increased. Such measures were probably taken at the time when they were built, and formed part of a network of watering sites along transhumance routes (van Wesemael et al., 1998).

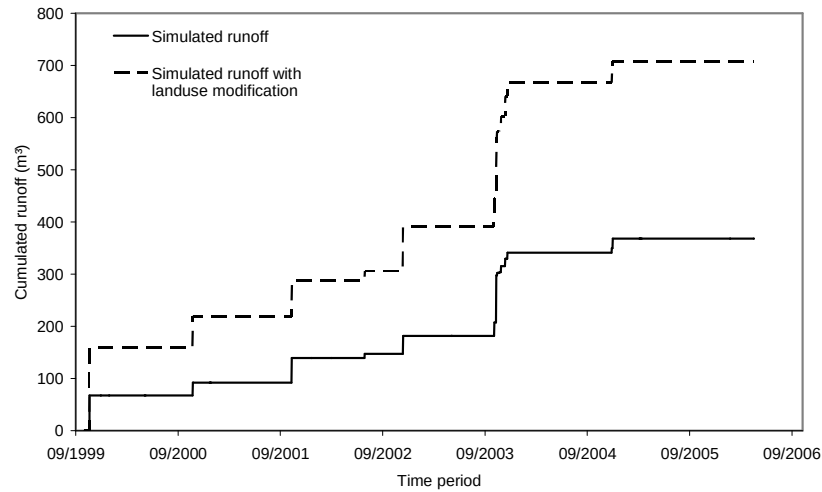


Figure 4.7. Comparison between Stream model results for simulated cumulated runoff volume over seven year.

4.4. Conclusions

The runoff response of hillslopes in semi arid rangelands (Sierra de Gador; south east Spain) was greatly influenced by connectivity between response units. Rainfall/runoff models have to take the high spatial heterogeneity of surface conditions into account in order to predict runoff volume. The STREAM model provides the hydrological network and evaluates the runoff connections in function of the antecedent moisture conditions, rainfall characteristics and hydrological response of the soil surface. After adaptation of the decision rules to the local climate conditions, such as antecedent soil moisture and duration of the storm, and the attribution of final infiltration rates to the hydrological response units, the STREAM model proved to be able to predict the runoff from 0.4 to 6 ha hillslopes of individual events with a reasonable accuracy ($RMSE = 13.9 \text{ m}^3$) and only a slight tendency for overestimation ($ME = 2.3 \text{ m}^3$). Given the large variability in annual runoff observed ranging from 0 to 172 m^3 and the low number of events per year, the uncertainties ($RMSE$) are acceptable for the estimation of the effectiveness of water harvesting systems. The results confirm the strong sensitivity of the

model to variation in storm duration. Hence, the length of the storms needs to be defined according to local climate conditions. The use of total storm rainfall during the period for which the intensity is higher than 5 mm h^{-1} t_{eff} gave the best results. The classification of the soil surface characteristics (i.e. rock outcrop and vegetation cover) and the attribution of a unique set of hydrological parameters to each class will then allow the prediction of runoff from any hillslope within the same region and under the same land use. Model simulations show that small modifications of land cover such as vegetation and sealing within flow paths enhance significantly the effectiveness of water harvesting systems.

Chapter 5

The contribution of runoff to recharge rates in a semiarid to subhumid carbonated aquifer.

Outline

Two general pathways exist for recharge in carbonated aquifers: i) diffuse percolation from the base of the soil profile and ii) concentrated infiltration of surface water in favourable zones such as ephemeral stream beds and widened cracks in partly dissolved limestone. It has been shown that for large semi arid regions diffuse percolation can be assessed from the water balance i.e. the difference in precipitation and evapotranspiration. Recently, methods have been developed to assess the water balance at the regional scale based on the spatial distribution of rainfall and vegetation indices, the latter as a proxy for evapotranspiration. Concentration of surface water occurs during moderate to heavy rainfall events as a result of runoff generation from impermeable or low permeable areas, or partially controlled by slope when permeable rock outcrops. It has been shown that the large carbonate aquifer system of the Sierra de Gador, underlain by the Campo de Dalias coastal plain, is fed preferentially during storms with a return period of more than 1-5 years. However, as a result of the volume of the aquifer, its unknown response time and the infrequent occurrence of such events, no evaluation of the relative contribution of diffuse versus concentrated recharge can be made. Therefore, different methodological approaches are applied to assess the role that both type of recharge mechanisms (diffuse and concentrated) have on the water yield of a single semiarid catchment which is drained by the spring of Celin. The

study catchment covers a surface of c.26 km² ranging from the footslopes at 580 m a.s.l. to the summit of the Sierra de Gador at 2200 m a.s.l. The average potential recharge varies from more than 250 mm/year in the highest part of the catchment to less than 50 mm/year in the bottom of the range. Runoff was calculated using a spatially distributed rainfall/runoff model that was calibrated on water harvesting systems draining the representative combination of vegetation, rock outcrop and soil types within the Sierra de Gador. An altitudinal gradient of runoff to concavities and stream beds was calculated for moderate storms (return period 0.1, 0.25, 0.5 and 1 year) under wet, normal and dry antecedent moisture conditions in order to estimate concentrated recharge. Furthermore, gradients as a result of diffuse recharge based on the spatial modelling of the water balance will be calculated based on the method of Contreras et al. (2008). Both gradients will be checked with those obtained by isotopic techniques, focussed to know the source of recharge, and by conservative chemical balances to quantify diffuse recharge rates in local springs at several altitudes. Under steady-state conditions, the bulk solutes mass discharged in Celin spring integrates flow mass derived from diffuse recharge by rainfall at several altitudes plus mass flow from concentrated recharge by runoff. Isotopic methods and the chloride mass balance give a recharge rate of about 4.25 hm³ per year. The mean annual infiltration is estimated at about 0.4 hm³ per year. These results give more insights about the relative contribution of both pathways to recharge in semiarid carbonate aquifers which contribute to about 10% of the total recharge. An understanding of the relative contribution of these pathways along altitude is essential for implementing measures to increase recharge artificially.

5.1 Introduction

In semi arid limestone areas, the only available water resource is provided by ground water. Therefore, a sustainable management of the water resources should be based on correct estimation of the recharge volume. The evaluation of recharge rates of a karst limestone aquifer in semi arid area is complex and is usually limited to a global estimate using isotopes or tracers (Hugues et al., 2008; DeVries and Simmers, 2002; Scanlon et al., 2006). Such approaches do not provide information on the spatial and temporal distribution of recharge and the occurrence of hotspots where runoff concentrates and provides large volumes of water that are less likely to be retained in the soil and subsequently lost through evapotranspiration. Alternatively, an ecohydrological approach based on a spatially distributed seasonal water balance does provide information on the major recharge zones, but does not provide an insight on the role of individual storms (Boer et al. 1999, Contreras et al., 2008). Since, it has been shown that karstic aquifers in a semi-arid region is mainly recharged by storms with a return period of more than 1 year (Frot et al., 2007), one can assume that during storms the percolation will not be uniform, but at least one fraction of the precipitation will produce runoff and increase percolation in valley bottoms. Determining the contribution of runoff to recharge and determining its spatial pattern will be valuable tools to protect or increase the recharge of the aquifer. A modelling approach was realised by implementing a distributed hydrological model, MIKE SHE, to the semi-arid Andarax River basin, SE Spain, to examine the hydrological behaviour and to assess the water resources (Van Cauwenbergh, 2008). Particular emphasis is given to the simulation of the seasonal and spatial distribution of recharge within the river catchment. Results give correct estimates and show larger discrepancies between observations and simulations than usually seen for more temperate hydrological regimes (Andersen et al., 2008). The mean recharge corresponds to 6 % of the precipitation (Andersen et al., 2008).

In semi-arid areas, runoff is erratic with high spatial and temporal transmission losses (Yair 1992; Bergkamp et al., 1999), and discontinuous patterns (Pilgrim et al., 1988; Western et al., 2001). Precipitation and antecedent moisture conditions characteristics act as thresholds in runoff production (Cammeraat, 2004 and Frot et al., 2008). Nevertheless, previous studies have shown the predominant influence of the landcover on runoff and the importance of the spatial distribution of areas with low infiltration capacities (such as bare soil and rock outcrops) and vegetated areas (Bergkamp et al., 1999; Puigdefabregas, 2005, Frot et van Wesemael, 2009). In mountainous areas, the influence of topography and variability of soil properties on recharge are most significant (Wilson and Guan, 2004).

Moreover, in semi-arid karstic areas one of the difficulties to quantify recharge rates is related to the complex geology where two flow systems occurs (i.e. bedrock hydraulic conductivity and percolation through fractures). Nevertheless, linked to the semi arid climate, the regular monitoring of discharge is often not possible and precipitation is spatially and temporally highly variable.

Several factors and processes are involved to explain recharge rates in semi-arid areas. Recharge processes are directly linked with vegetation whose density affects the infiltration capacity and evapotranspiration rates (DeVries and Simmers, 2002). The total rainfall amount is frequently used to estimate recharge by means of long term water balances and provides satisfactory results (Boer et al., 1999, Contreras et al., 2008). However, the role of rainfall intensity, concentration and infiltration of runoff water are increasingly put forward (Hugues et al., 2008). DeVries and Simmers (2002) and Scanlon et al. (2006) wrote an overview of processes, recharge rates of aquifer recharge in semi-arid areas. They indicate the non negligible recharge from the percolation of concentrated surface water. Especially, in semi-arid areas where potential evapotranspiration is high and recharge can occur during extreme rainfall events producing concentrated surface water in depressions, cracks and

streams. Recent studies attempt to understand and characterize the spatial distribution of transmission losses through the ephemeral stream beds and their contribution to recharge (Callegary et al., 2007; Coes and Pool, 2005; Lange et al., 2005). The most frequently used techniques to quantify recharge in semi-arid regions are: i) the chloride mass-balance based on the conservative properties of the chloride ion, ii) the long-term water balance and iii) stable water isotopes, such as $\delta^{18}\text{O}$, that allow identifying the origin of air masses of precipitation, recharge areas and processes of recharge (Scanlon et al., 2006). Due to incertitude linked to recharge estimations the use of several method is generally adopted.

In semi-arid areas, runoff is generally considered as negligible and therefore recharge along concentrated surface water in this environment has received less attention. The originality of this study is to extrapolate rainfall/runoff data obtained at the hillslope scale to the regional. In this chapter, an attempt was made to quantify the contribution of this type of recharge. The recharge rates assessment from concentrated infiltration of surface water is focussed on a single spring of Celin for which long term average estimations of recharge rates and isotopic and chloride mass balance techniques were applied. The use of distributed model enables us to improve its estimates and assess the recharge rates from concentrated flow. The aim of this study is to extrapolate a rainfall/runoff model calibrated and validated at the hillslope scale in order to estimate recharge rates from runoff concentrated in zones that are likely to favour percolation. The results will be compared to the recharge rates with other approaches and then to identify the main recharge area.

5.2 Material and methods

5.2.1. Site descriptions

As headwaters are generally recognized for their role as recharge areas, the research focused on one of the 55 small basins on the southern slopes of the Sierra de Gador ranging between 1 to 54 km². The catchment of Celin is well-defined and it was chosen since isotopic and chemical data were available from the spring water (Contreras et al., 2008; Alcala et al., 2007; Alcala, 2006) (Fig. 5.1). The catchment covers a surface of c.26 km² ranging from the footslopes at 580 m a.s.l. to the summit of the Sierra de Gador at 2200 m a.s.l. and represents 7% of the effective reservoir volume of the hydrological complex of Sierra de Gador – Campo de Dalias aquifer (Martin-Rosales et al., 2007) (Fig. 5.2a). The spring of Celin is on the southern slope of the Sierra de Gador (Fig. 5.1) and its catchment consists mainly of carbonated rocks (limestones and dolomites). The Celin catchment has steep slopes and a dendritic ephemeral stream network, locally referred to as ramblas. The catchment is dominated by rangeland consisting of herbaceous plants, shrubs and matorral vegetation. On the foot slopes, the vegetation is denser and trees such as pines are growing along the depressions. On the summit, the soil is thin and rocky (generally < 0.2 m) and mainly consists of rendzic and mollic Leptosols (FAO soil group), on the depression the soil have a thickness of 50cm. At the middle range of the catchment, in the depression developed in colluviums, soils are more calcic with a thickness which may vary between 30-70 cm (Katanozems, FAO soil group) (Contreras, 2006). Precipitation increases from 196 mm in the lower parts (Almeria) to 670 mm on the summit due to a strong orographic effect (Lazaro et al., 2001). Precipitation mainly occurs during winter periods and evapotranspiration is evaluated at 69% of the annual precipitation (Contreras et al., 2008). The average potential recharge varies from more than 250 mm y⁻¹ in the highest parts of the catchment to less than 50 mmy⁻¹ in the bottom of the range.

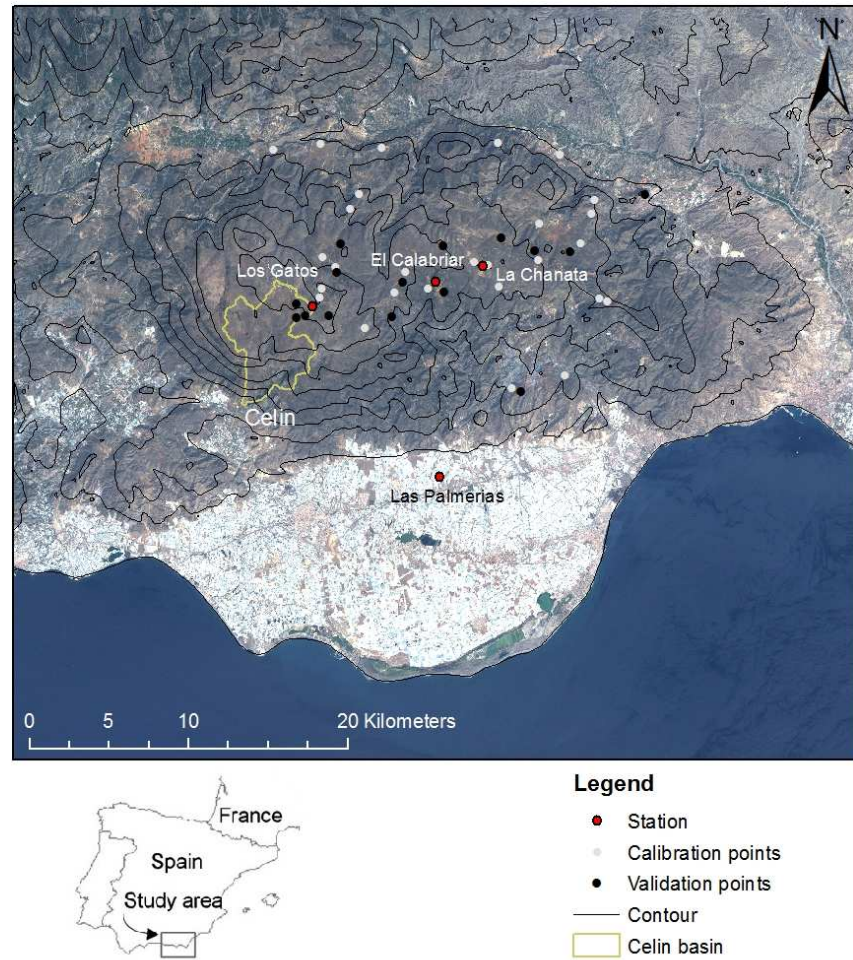


Figure 5.1. Localisation of the Sierra de Gador and Celin catchment. Calibration and validation points use for the parameterisation of hydrological response units.

5.2.2. Model

Expert-based model: STREAM

The STREAM is a spatially distributed expert-based model approach (Cerdan et al., 2002a,b). The model estimates the infiltration/runoff balance ($B\alpha$) for each pixel, the pixel size depends on the resolution of the DEM (Eq. 5.1).

$$B\alpha = P - ST - (I\alpha \times t) \quad 5.1$$

Where P is the rainfall depth (mm); ST the initial soil storage (mm); $I\alpha$ is the infiltration capacity (mm h^{-1}) of the pixel α and t is the rainfall duration (h).

The model is not dynamic and runs on an event basis. It is based on the dominant processes which results from decision rules established for the main parameters. Stream runs in a GIS and allows a direct visualisation of the runoff flow network and runoff/infiltration balance presented as maps (Souchère et al., 1998; Cerdan et al., 2002a, b). At the event based for which the model runs, evapotranspiration is considered to be negligible, and only the antecedent moisture conditions are taking into account. Input data for the STREAM model consist of (i) a digital elevation model (DEM) for the determination of the runoff routing (ii) a spatial description of the vegetation and rock outcrop cover defining the hydrological response units (iii) precipitation (depth and duration) and (iv) antecedent precipitation index (API).

DEM

The DEM of the catchment has a resolution of 10 m (Junta de Andalucía, 2005) (Fig. 5.2a). For each pixel the model evaluates the upslope runoff and the runoff generated on the pixel itself combining with the flow accumulation, runoff flow network is calculated. The infiltration generated on the pixel is also calculated.

Predicted runoff at the hillslope scale and extrapolation to the catchment

Runoff in the Sierra de Gador was studied in three water harvesting systems draining hillslopes (0.4 ha – 6 ha) using a 7-year dataset (Frot et al., 2008). The model has been adapted for a semi arid area, calibrated and validated on water harvesting systems draining the representative combinations of vegetation, rock outcrop and soil types within the Sierra de Gador (Frot &

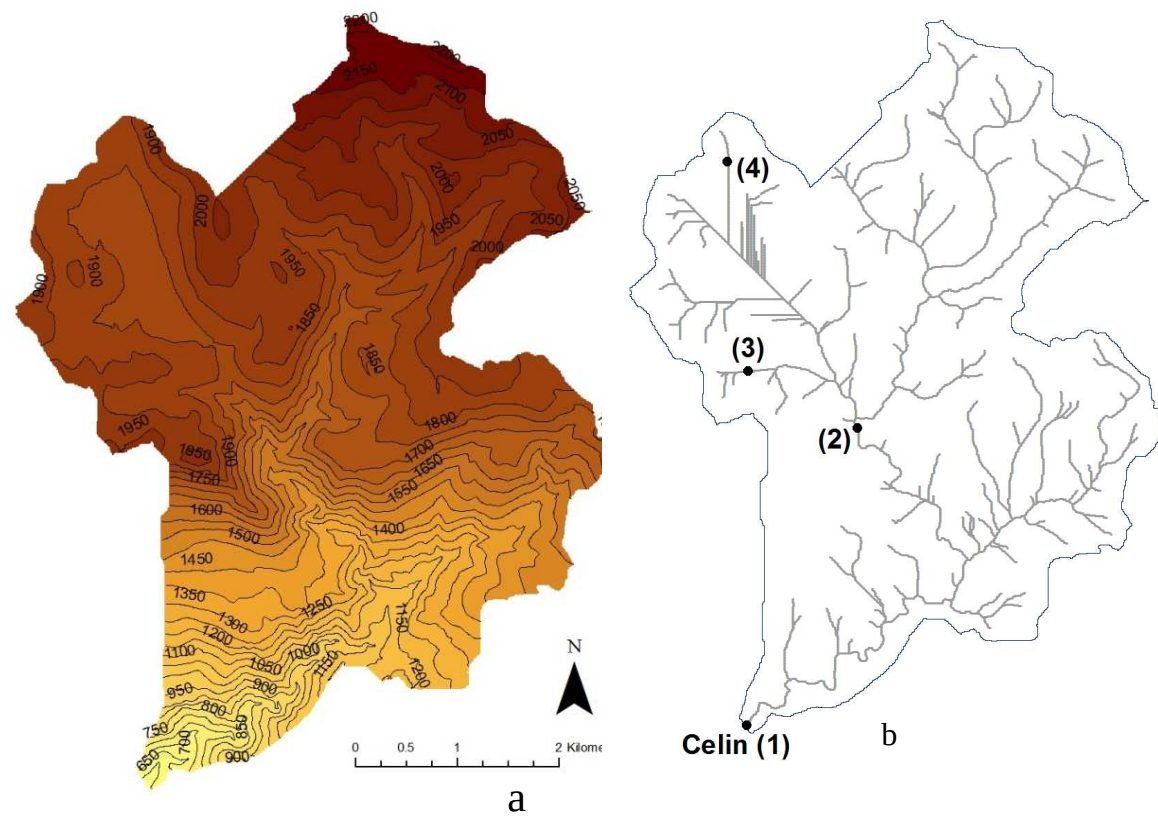


Figure 5.2. Characteristics of the study area. (a) DEM; (b) drainage network; 1,2,3,4 dots are site of interest.

van Wesemael, 2009) (Table 5.1). The spatial pattern of the runoff and quantities predicted in function of the precipitation and antecedent moisture conditions and land cover described by the hydrological response units provide acceptable results ($RMSE = 13.9 \text{ m}^3$) given the large variability in annual runoff observed ranging from 0 to 172 m^3 and the low number of events per year (Frot & van Wesemael, 2009). Whereas, no upscaling procedure was realised in this thesis. Hydraulic properties are known to be scale dependent and in order to limit scale effect we calibrated and validated the model stream for 3 hillslopes for which the pixel size was 1 m (Era Vicario), 2m (El Calabriar) and 3m (la Chanata). For the application at the basin scale the pixel size was 10m. Results may be somewhat overestimated.

5.2.3 Model parameters

In order to extrapolate from the hillslope to the catchment, some parameters obtained at the hillslope scale will be used (infiltration capacity, initial soil storage (ST), antecedent precipitation index), while for others a spatial distribution will be used (Hydrological response units, precipitation).

The infiltration capacities ($I\alpha$) and ST attributed to each response units were calibrated and validated on water harvesting system within the Sierra de Gador in a previous study (Frot and van Wesemael, 2009) (Table 5.1). The classification to define the response units are based on rock outcrop and vegetation cover, the two main parameters that describe the infiltration capacities. Three class intervals of rock outcrop and vegetation cover percentage were used: 0-30%, 30-50% and more than 50% and combined to define five classes of landcover (Table. 5.1).

Three antecedent precipitation index (API) were used (Frot et al., 2007 and Frot & van Wesemael, 2009). No data was available to define spatial patterns of soil moisture content within the catchment. Hence, antecedent moisture conditions were considered uniformly over the watershed.

Table 5.1. Hydrological Response Units defined according to rock outcrop and vegetation cover with the corresponding NDVI value, final infiltration capacity and initial soil storage. (Table based on Frot and van Wesemael, 2009).

Classes	NDVI	Rock outcrop cover (%)	Vegetation cover (%)	Infiltrability (mm/h)	Initial Soil Storage (mm)		
					API 1 ^a	API 2 ^b	API 3 ^c
0	>-0.096	> 50	0-30	2	6	3	0
1	-0.096	30-50	0-30	6.5	15	8	0
2	-0.024	0-30	0-30	12	40	18	0
3	0.009	0-30	30-50	40	60	40	0
4	0.129	0-30	> 50	90	100	60	1

^aAPI 1 : API < 7.6 mm

^bAPI 2 : API = 7.7 to 28 mm

^cAPI 3 : API > 28.1 mm

Hydrological response units

Hydrological response units were defined through a set of indicators that influenced the final infiltration capacities (Imeson et al., 1992; Yair, 1992; Cerda, 1995; Bergkamp et al., 1996; Bull et al., 2003; Cammeraat et al., 2004). Previous studies have shown that in the study area the pattern of the vegetation and rock outcrop cover greatly influence infiltration rates (Li et al., 2008; Frot et al., 2008). The spatial pattern of the vegetation is estimated by the Normalised Difference Vegetation Index (NDVI), the most widely used vegetation indices (Rouse et al., 1974). NDVI is a dimensionless index that is indicative for vegetation photosynthetic activity (eq. 5.2).

$$NDVI = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} \quad 5.2$$

where ρ_1 is the reflectance of red light (0.61-0.68 μm) and ρ_2 is the near-infrared reflectance (0.78 -0.89 μm).

NDVI varies according to vegetation type and season (Diaz-Delgado et al., 2002 and Ruiz-Gallardo et al., 2004). The signal will be a mixture of vegetation, bare soil and shadow and NDVI has a continuous range of from -1 to 1 . Rock and bare soil have similar indices of reflection in these two bands and produce a vegetation index close to zero.

The delimitation of the hydrological response units is derived from SPOT image with 20m resolution. The NDVI were calculated from orthorectified SPOT image acquired in 25/10/2001. This period was chosen since it corresponds to the moment of the year when precipitation is most abundant and therefore recharge is likely to occur. Spatial variation of soil surface cover was assessed along 42 geo-referenced control points throughout the Sierra de Gador (Fig. 5.1). From the centre of the control point transects of 50 m were established to the North, North East, East, South, South West and West at 1m intervals the surface cover was noted. Furthermore, 100 observations were carried out on a 1m² surface based on a 10 cm grid. Each time the surface cover was recorded in one of the following categories: vegetation, stoniness, rock outcrop and bare soil. Field samples with land cover descriptions are used to calibrate and validate the spatial description with the NDVI values. Randomly selected, 27 of the control points are used as calibration points and 15 are the validation points.

Spatially distributed rainfall

The study area has a steep gradient ranging from the footslopes at 580 m a.s.l. to the summit of the Sierra de Gador at 2200 m a.s.l (Fig. 5.2a). Therefore, there is an altitudinal gradient in rainfall. For each storm a spatial estimate per pixel of the rainfall depth is required to take into account the difference in rainfall from bottom to summit of the catchment. The meteorological stations on the southern slopes of the Sierra the Gador were used to evaluate the rainfall gradient: meteorological station of Las Palmerillas (151 m asl) and local rain gauge stations of La Chanta (1418 m asl), El Calabriar (1350 m asl) and Los Gatos (2005 m asl). The rainfall duration was considered constant along the slope. The effective rainfall duration (t_{eff}) was described as the most appropriate rainfall duration for the study area (Frot and van Wesemael, 2009).

The stream model estimates the rainfall intensity by considering the rainfall depth for the rainfall duration and t_{eff} allows redefining the rainfall duration for which the rainfall is supposed to be more aggressive. t_{eff} was defined as the rainfall event duration re-evaluated as a function of the percentage of rainfall amount with intensity larger than 5 mm.h⁻¹ (eq. 5.3).

$$t_{\text{eff}} = t_5 + (t_{\text{tot}} - t_5) \times \left(1 - \frac{P_5}{P}\right) \quad 5.3$$

For a storm with intensity always lower or always higher than 5 mm.h⁻¹, the effective rainfall duration is considered as the total rainfall duration.

5.2.4 Running the model

Defining zones of concentrated runoff

In order to avoid taking into account the retention of soil moisture that will be subsequently lost to the atmosphere by evapotranspiration, we restricted the areas for which recharge rates will be calculated. Areas of concentration have been identified as a surface which drains a minimum 0.025 km² (250 pixels of 10 m² of resolution). This area in the valley bottoms of the Celin catchment has a surface of 0.67 km² representing 2.6% of the total basin area. The physical characteristics of the runoff concentrated areas have not been calculated precisely, the width (one pixel) is considered as constant from upstream to downstream. The river network, as defined by the minimum drainage area given above, will be used to calculate the total amount of infiltrated water (Fig. 5.2b).

Event based and yearly runoff

First, the model will be run on the Celin catchment for storms that are typical for the region. Precipitation with a return period corresponding to local climate were selected (T in years) (i.e. P=10 -25 mm for T = 0.1 year; P=25 - 58 mm for T = 0.25 year; P=40 – 90 mm for T = 0.5 year and P=48 – 105 mm

for $T = 1$ year). Note that an event with a fixed return period will show an altitudinal gradient in precipitation). The duration of events are those recorded in the study area (i.e. mean rainfall duration = 5 hours, long rainfall event = 8.5 hours and short rainfall event = 1.4 hours) and antecedent moisture conditions described as dry (API1), moderate (API2) to humid (API3). Then, the STREAM model will be applied for 3 contrasted hydrological years (average 1999-2000, wet 2003-2004 and a dry year for 2004-2005) recorded in the study area in order to estimate average recharge rates. The model is event based and the yearly runoff is obtained by the sum of all simulated runoff events.

5.3 Results and discussion

5.3.1 Parameterization of the regional model

Hydrological response units

The land cover of the Celin catchment is provided by the classification of the NDVI image. The classification of the land cover follows the five classes of hydrological response units defined in a previous study (Frot and van Wesemael, 2009). Vegetation percentage was plotted against the NDVI value of the ground control points selected for the calibration (Fig. 5.3) (eq. 5.4).

$$\text{NDVI} = 0.01 \cdot \text{Vegetation} + 0.017 \quad 5.4$$

The estimation performances are satisfactory with an r^2 of 0.5. The classes 4 and 3 were easily defined in function of the percentage of vegetation (Fig. 5.3 and Table 5.2). Whereas, a NDVI of 0 correspond to sites with no vegetation mainly bare soil and rock outcrops. To distinguish the three others classes, the mean NDVI value was calculated in function of the type of dominant land cover (Table 5.1). Field validation points were used to validate the classification and the accuracy is given by the root mean square error (RMSE) for the ground control validation points is 12 % of vegetation cover (Fig. 5.4). Hence, five classes are defined in Table 5.2 and used to classify the NDVI image of the Celin catchment (Fig. 5.5).

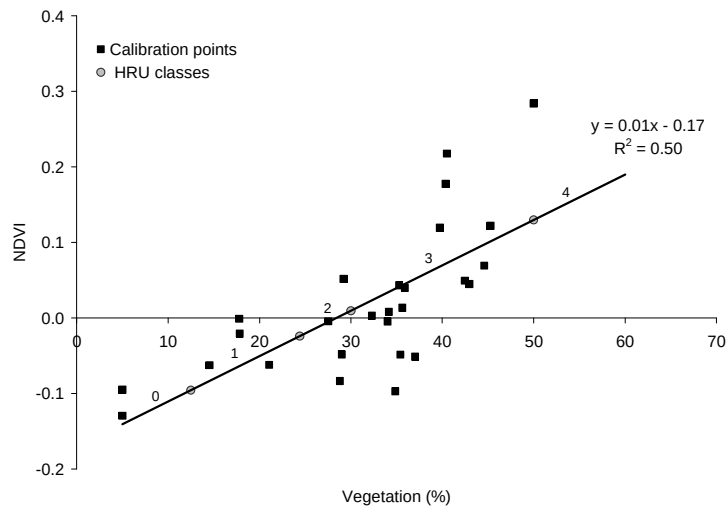


Figure 5.3. NDVI versus vegetation percentage of the ground-control points situated on the Sierra de Gador. Classes of the hydrological response units were defined in Table 5.1.

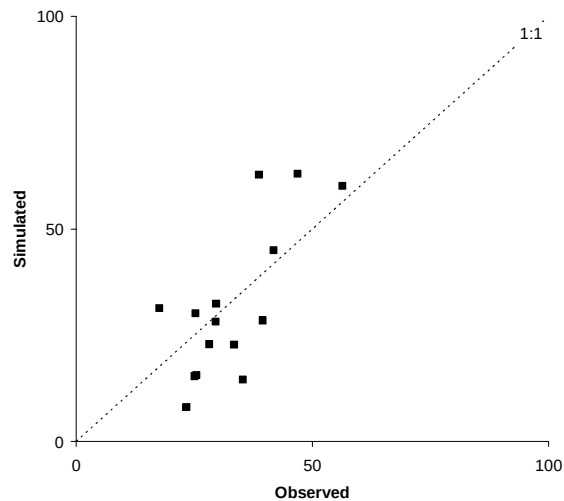


Figure 5.4. Observed versus simulated vegetation percentage estimated by the NDVI/vegetation model.

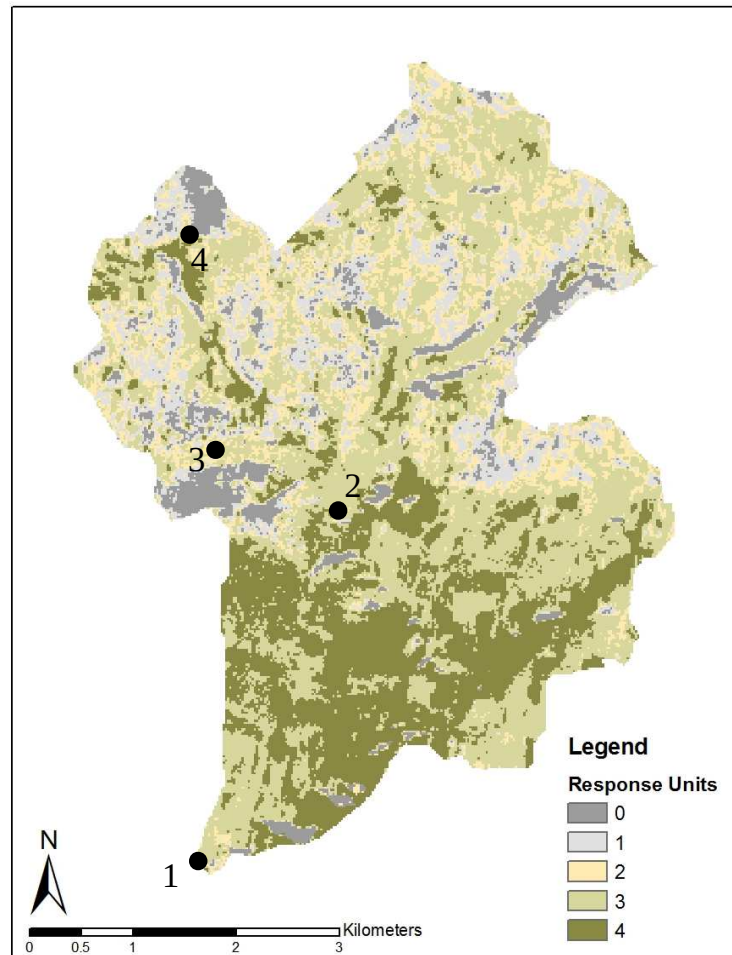


Figure 5.5. Hydrological response units of the Celin catchment. Classes are defined in the Table 5.1. 1, 2, 3, 4 dots are site of interest.

Precipitation

Due to the large altitudinal gradient observed in the Celin catchment, the precipitation depth shows large variation in function of the elevation. Four meteorological stations at different altitudes were used to find a simple relationship between elevation and precipitation at the event scale. We have not enough rainfall data in common to establish a simple relation between rainfall

and elevation for three local stations on the sierra and the meteorological stations of Las Palmerillas. Therefore, first simple relation was established between each local station of the Sierra and Las Palmerillas and secondly, to substitute these three relations in one linear relationship. The aim is to calculate a precipitation depth of a single storm for each pixel of the digital elevation (Rz) model as a function of altitude (Z) for the corresponding rainfall amount recorded at the meteorological station of Las Palmerillas (Pp). First linear relationships were fitted between the rainfall depth of Las Palmerillas (151 m) and three other local stations (i.e. La Chanata at 1418 m a.s.l, El Calabriar at 1350 m a.s.l and Los Gatos at 2005m a.s.l). Based on these relations, precipitation amounts, corresponding to rainfall events of respectively 10, 20, 30, 40, 50 mm in Las Palmerillas, are estimated for each of this three stations. Next, for each of the latter rainfall events regressions (eq. 5.4) were obtained between altitude and rainfall quantities calculated for the different stations (Table 5.2).

$$P_z = a \cdot Z + b \quad 5.4$$

where Pz is rainfall depth (mm) at the altitude Z (m). This allows us to express the parameters (a, b) of these regressions as function of precipitation amount at Las Palmerillas.

$$\text{Regression on a parameter } a = 0,0008 P_p + 0,0009 \quad 5.5$$

$$\text{Regression on b parameter } b = 0,7349 P_p - 0,6048 \quad 5.6$$

where Pp is the rainfall depth at the station of Las Palmerillas.

Table 5.2. Regression parameters (eq. 5.4) for rainfall events in the local meteorological station of Las Palmerillas (151m a.s.l) estimated by three local stations (i.e. La Chanata at 1418 m a.s.l, El Calabriar at 1350 m a.s.l and Los Gatos at 2005 m a.s.l).

	10	20	30	40	50
a	0.009	0.018	0.026	0.035	0.043
b	6.74	14.09	21.44	28.79	36.14
r ²	0.83	0.85	0.86	0.86	0.87

Finally, by substituting eq.5 and eq.6 into eq.4 rainfall can be estimated for a given altitude and rainfall quantity at Las Palmerillas chosen as reference station (eq. 7)

$$P_z = (0.0008 \cdot P_p + 0.0009) \cdot Z + 0.7349 \cdot P_p - 0.6048 \quad 5.7$$

5.3.2 Spatial distribution and evaluation of transmission losses

In semi-arid areas, stream beds are characterized by ephemeral flow while most of the concentrated water infiltrates rapidly in the channel bed (Yair 1992; Bergkamp et al., 1999; Arnau-Rosalen et al., 2008). Most of the time, storms do not produce runoff but the ramblas can become very active for a limited number of events and can produce flood events (Martin-Rosales et al., 2007). Modelling results show that flow in the ephemeral stream network is rare and occurs less than four times per year on average (Fig. 5.6). An important threshold in precipitation and antecedent moisture conditions needs to be reached before runoff reaches the stream network. A storm with a return period of 6 months is necessary to produce runoff at the outlet of Celin (Table 5.3).

Three simulations with storms of different return periods (i.e. 3 months, 6 months and 1 year) illustrate both the areas where runoff is preferentially produced and where infiltration occurs (Fig. 5.6). With increasing intensity of the storms the runoff network gradually extends from the top of the catchment, where the rainfall volumes are highest and the infiltrability is lowest (see areas around 3 and 4 in Fig. 5.5), to the outlet. For moderate events, runoff is limited to the areas where rock outcrops occur and areas around 3 and 4 in Fig. 5.6a have the highest discharges (Table 5.3), then runoff starts to concentrate in the streambed and infiltrates downstream with the maximum discharge around site 2 (Fig. 5.6b and Table 5.3). Finally, the connectivity

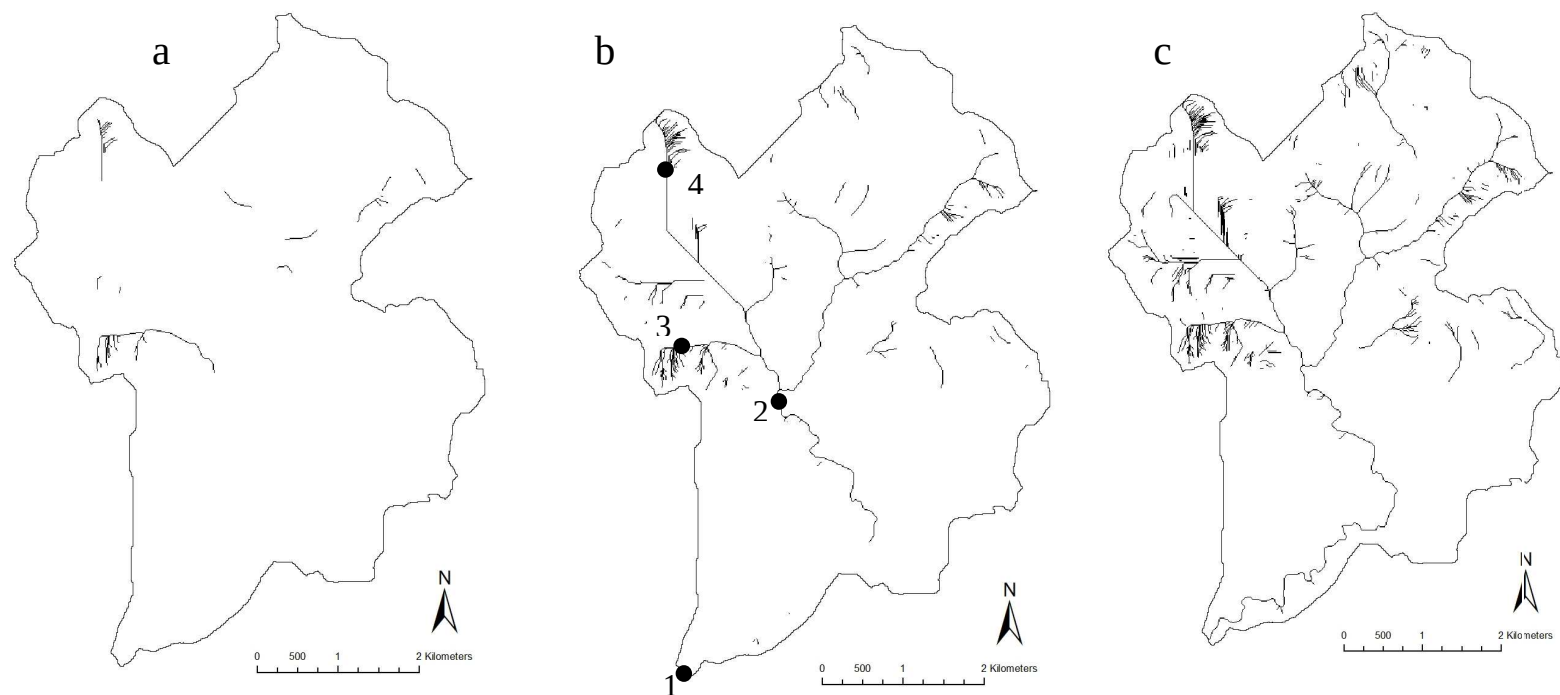


Figure 5.6. Example of simulated runoff patterns for the Celin catchment. Simulated runoff was obtained for three rainfall events (a : $T = 0.25$ year; b= $T = 0.5$ year; c: $T = 1$ year) with $t_{\text{eff}} = 8.5\text{h}$ and $\text{API} = 3$. 1,2,3,4 dots are site of interest.

Table 5.3. Modelling results. Runoff and infiltration rates into the ephemeral stream bed (described in figure 2b) for 4 precipitations of different return period ($T = 0.1, 0.25, 0.5$ and 1Year) for a mean rainfall duration of 5 hours ($t_{eff} = 5$ hours).

Precipitation Return period (year)	API	R_{max}^a (m ³)	R_{outlet}^b (m ³)	Infiltration (m ³)	Total ^c (m ³)	Maximum runoff site ^d
0.1	1	140	0	14151	14151	4
0.1	2	251	0	14488	14488	4
0.1	3	648	0	15838	15838	4
0.25	1	4348	0	46479	46479	3
0.25	2	5933	0	56822	56822	3
0.25	3	16943	0	75561	75561	2
0.5	1	37834	15348	108706	124054	2
0.5	2	65287	45201	107692	152893	2
0.5	3	118092	101803	105116	206919	2
1	1	87730	66837	122460	189296	2
1	2	134337	115975	122953	238928	2
1	3	206266	193416	118536	311952	1

a Maximum runoff (m³)

b Runoff at the outlet (m³)

c Total R outlet + Infiltration rates (m³)

d maximum runoff site (1,2,3,4) shown in figure 2

throughout the catchment is reached during the 1 year event and the highest discharge is reached at the outlet (Fig. 5.6c and Table 5.3). Hence, concentration of surface water occurs during moderate to heavy rainfall events as a result of runoff from areas with low permeability that is sufficient to reach the bottom of the hillslopes when the soils are moist to humid (Api2, Api3) as often occurs during the winter period. Similar patterns of runoff and infiltration were observed on semi arid hillslopes (e.g. Yair and Raz-Yassif, 2004; Frot & van Wesemael, 2009). In dry conditions, the first runoff predicted is only obtained for a rainfall event of 3 month return period that falls as a short outburst ($t_{eff} = 1.4$ hours) which is rare. More likely, a 6 months return period event with an average duration will produce continuous runoff in dry condition

to the extent of producing a continuous network (Table 5.3 and Fig. 5.6b). Vegetated zones are mainly located downstream and act as main infiltrated areas where no runoff is produced (Fig. 5.5 & 5.6).

The volume of runoff at the outlet is generally low compared to the amount of rainfall received, taking into account the increase in rainfall with altitude (eq. 5.7). For instance, runoff at the outlet for a rainfall event with a return period of 6 months (P ranging between 40 to 90 mm in 5 hours, totalling 1.86 hm^3) produces 0.05 hm^3 in moderate and humid antecedent moisture condition respectively, a volume of to 0.10 hm^3 (Table 5.3). An event with a return period of one year (P ranging between 48 to 105 mm in 5 hours, totalling 2.24 hm^3) produce in moderate to humid antecedent conditions to the outlet a runoff of 0.12 to 0.19 hm^3 (Table 5.3). Martin-Rosales et al. (2007) used different approach in order to calculate runoff of a dam somewhat upstream of the Celin spring (catchment area 23.2 km^2). They used a fixed rainfall amount for the entire catchment combined with area weighted runoff coefficients within the SCS curve number methodology. This approach can lead to completely different results. The rainfall depth of their 5 year event ($P=76 \text{ mm}$ totalling 1.75 hm^3 for the entire catchment) was similar to the event we used as a 6 months event, and the discharge (0.25 hm^3) predicted was nearly twice as high. The lack of spatialisation in both rainfall depths therefore results in much lower rainfall volumes over the entire catchment while the use of an average runoff coefficient strongly increases the discharge for moderate events. Many authors already showed that estimates of runoff based on area weighted averages of curve numbers do not take into account the contrasts in infiltrability and therefore not suitable in semi arid areas in general (e.g. Meerkerk et al., 2009) and even less in karstic areas (Frot & van Wesemael, 2009). Although the spatial distribution of the rainfall and the infiltration capacity can certainly be improved, the thresholds for the development of connectivity as well as the increase in connectivity with event size are coherent

with the literature on rainfall/runoff in semi-arid regions (Cammeraat, 2004; Yair and Raz-Yassif 2004; Meerkerk et al., 2009).

5.3.3 Recharge rates in the Sierra de Gador

Although we have demonstrated in the previous section that runoff rarely occurs and that during all storms simulated there is a considerable loss of runoff in the stream beds. The concentration of runoff results in deep percolation and probably to a large extent recharge as the proportion of moisture lost to evapotranspiration in these zones of concentrated runoff is probably insignificant. Therefore, runoff and infiltration in the streambeds were calculated for all storms in a dry ($P = 270$ mm), normal ($P = 411$ mm) and wet year ($P = 675$ mm; precipitation in La Chanata, Fig. 5.1 & Table 5.4). The mean annual infiltration is estimated at about 0.4 hm^3 per year, ranging to 0.23 hm^3 in a dry year to 0.61 hm^3 in wet year. The annual runoff expected is 0.08 hm^3 which represent about 20% of the infiltration rates.

In order to evaluate the relative importance of the infiltration in the zones of concentrated runoff, three other independent approaches were compared to the results for the same study area: i) Stable water isotopes ($\delta^{18}\text{O}$) (Alcala et al., 2007), ii) chloride mass balance (Alcala et al., 2007 and Contreras et al., 2008) and a seasonal water balance approach (Contreras et al., 2008; Table 5.4). Isotopic methods give a recharge rate of 4.1 hm^3 per year and the assessment of the recharge rates from the chloride mass balance was around 4.4 hm^3 per year. Therefore, the recharge in the concentrated zones estimated in the present study represents about 10 % of the total recharge which may vary between 14.5% to 5.5% respectively for a wet to dry hydrological year. The long-term water balance (i.e. the difference in precipitation and evapotranspiration) gives a recharge rate of 5.7 hm^3 per year (Contreras et al., 2008). The authors using the latter method already mention the overestimation compared to the chloride mass balance method. The long-term water balance considered the hydrological year of 2003-2004 as normal which is effectively

normal comparing to the local meteorological station although over the 7 year of recording period (Frot et al., 2008) this year was particularly humid.

As Martin-Rosales et al., (2007) state that the Celin catchment represents about 7 % of the total recharge area, a global estimation from concentrated runoff (i.e. both infiltration and runoff) can be made by extrapolating the values obtained from Celin. This gives an average recharge of $5.9 \text{ hm}^3\text{year}^{-1}$ for the Sierra de Gador.

Table 5.4. Predicted annual infiltration and runoff rates for three hydrological years (normal 1999-2000, wet 2003-2004 and a dry year for 2004-2005). Results of estimated and measured recharge rates for the overall catchment of Celin.

Methods	Year	Infiltration $\text{hm}^3 \text{ yr}^{-1}$	Runoff hm^3	Recharge $\text{hm}^3 \text{ yr}^{-1}$
Stream model	99_00	0.35	0.063	0.4
	03_04	0.61	0.178	0.8
	04_05	0.23	0.001	0.2
Ecohydrological water balance (Contreras et al., 2008)				5.7
Isotopic methods (Alcala et al., 2007)				4.1
Chloride mass balance (Contreras et al., 2008)				4.4

5.3.4 Altitudinal recharge gradient

A non-linear relationship of the recharge rate with altitude is given for the study area (Contreras et al., 2008). Taking into account the surface area of the altitudinal bands, the recharge in hm^3 can be calculated (Fig. 5.7) both the long-term water balance and the recharge from concentrated flow show a peak between 1800-1900 m a.s.l (Fig. 5.7). This elevation for the bulk of the recharge is also obtained using the chloride mass balance and isotope methods (Contreras et al., 2008, Alcala et al., 2007). Several factors explain this area of recharge: i) the Sierra de Gador which has a plateau at the altitude of 1800 m

a.s.l., ii) 24% of the total surface of the stream beds is located at 1800m a.s.l. and 56% of the stream beds are located at an elevation higher than 1800m (Fig. 5.8), iii) at this elevation rainfall events are more important and frequent and iv). This zone has vegetation of low density as a result of the altitude and historical deforestation practices.

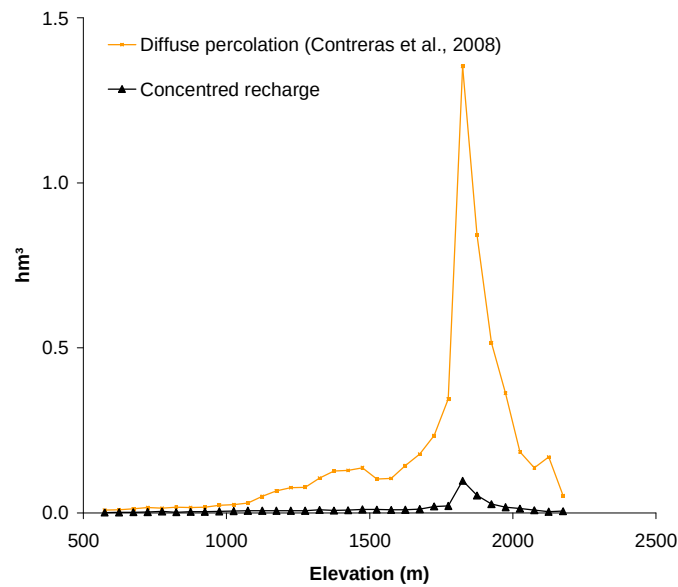


Figure 5.7. Diffuse and concentrated recharge versus elevation on the Celin catchment.

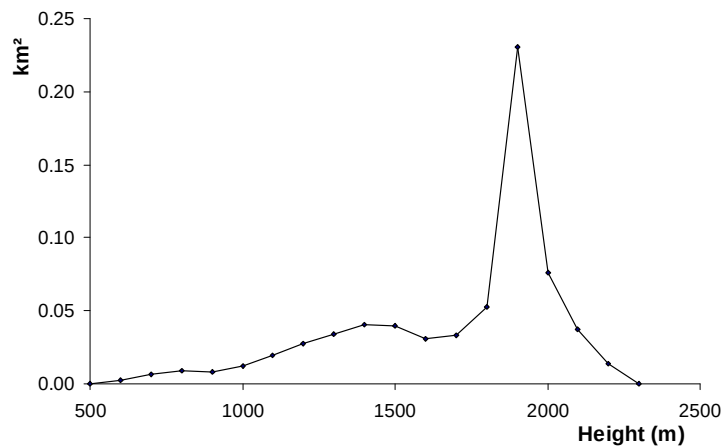


Figure 5.8. Surface area of the stream bed in function of altitude in the Celin catchment.

5.4 Conclusions

This chapter develops an approach to estimate recharge rates by concentrated runoff percolating in stream beds and to estimate the importance with respect to the total recharge obtained by independent methods cited in the literature. Infiltration in stream beds was estimated by extrapolation of a rainfall/runoff model calibrated and validated on three hillslopes in the mountain range under study with similar lithology and land cover. An adjustment on input parameters is proposed to consider spatially distributed rainfall and hydrological response units. The present study shows the ability of the Stream model to replicate transmission losses of runoff along a semi-arid catchment (26 km²).

The comparison of the model prediction with three different approaches (Ecohydrological water balance, isotopic method and Elevation-dependent chloride mass balance) allows us to estimate the relative contribution of concentrated runoff at around 10% of recharge rates. In addition, all approaches agree on the altitude where recharge mainly occurs (i.e above 1800 m a.s.l.). This corresponds to the broad crest of the Sierra de Gador.

These results indicate that a significant volume of water from concentrated runoff has an impact on groundwater recharge. The occurrence of significant recharge into stream beds stresses the need to much concern in water planning in those areas. The model could be used to test the influence of dams for example and could be helpful to select the best water management option. A long term perspective, considering the direct and indirect recharge of the groundwater would be to evaluate the impact of reforestation and land use changes in this area on groundwater recharge rates.

General conclusion

In a semi-arid limestone area, finding additional water resources is a priority. Moreover in the Sierra de Gador-Campo de Dalías, the local economy is booming and mainly based on groundwater resources. The study area is not an isolated case, other Mediterranean regions or semi-arid to arid regions are facing the same difficulties in balancing economic and natural resources. Aquifers are often overexploited and the demand is still growing. However, for sustainable development, water resources must be evaluated. Long term estimates based on global assessment of diffuse recharge is usually evaluated. Although extreme events are recognized to preferentially recharge the aquifer, no assessment of the contribution of such events to recharge was carried out in the study area. This thesis aims to contribute to the understanding of the groundwater recharge system (chapters 2 and 5) with particular attention for runoff processes (chapters 3, 4 and 5). This thesis focuses on the runoff as a component of water balance in semi arid areas. Runoff is generally regarded as negligible in the recharge system of the aquifer. Generally rare and discontinuous, the runoff processes is difficult to monitor. The approach we have used is to first evaluate the main factors explaining the occurrence of runoff reaching the bottom of the hillslope for several representative sites in the study area (chapter 3), then apply a simple rainfall/runoff model at the hillslope scale (0.3-20 ha) taking into account both characteristics of the storms and easily identifiable soil surface characteristics and finally, extrapolate this hillslope model to the catchment scale (26 km²; chapter 5) in order to estimate the impact of runoff as an additional source of surface and groundwater. The contribution of runoff to recharge was made by comparing the model results to the results of tracer techniques reported in the literature for the same catchment.

Main findings

Chapter 2 attempted to define the relationship between precipitation and groundwater for the study area. Such estimates improve the characterisation of the climatic context and more precisely precipitation origin and type of the study area. This chapter has allowed distinguishing origins of precipitation for the Iberian peninsula and has demonstrated the use of the deuterium excess (d -value) as parameter to determine the source of the water vapour that signs the origin of the precipitation. Precipitation is generated in two areas, the Atlantic Ocean ($d = 10\text{‰}$) and western Mediterranean basin ($d = 15\text{‰}$). In order to explain the type of precipitation events dominating recharge, stable water isotope values in precipitation from the Mediterranean basin and literature data were combined with isotopic data from aquifers in south east Spain. The total precipitation in the study area consists of storms from both origins. The monthly weighted d -value of precipitations is about 11.81‰ for the south and east coast of the Iberian peninsula. However, the d -value of the deep groundwater is around of 13.6‰ . The Mediterranean character of precipitation increases with monthly precipitation volume. These heavier storms mainly contribute to recharge, as it was expected and reported in the literature, extreme events have a major impact on the water resources. In order to identify the return period of the monthly rainfall supplying the deep groundwater, the d -values of Iberian peninsula precipitations have been compared with the d -value of precipitation at local meteorological station (at the middle range of the sierra). This selectivity of d to monthly precipitation was used to estimate the return period of precipitation leading to aquifer recharge. It was found that a return period at 0.9-4.9 years corresponds to the average composition of the groundwater. This implies that only a maximum of c. 40 % of the total precipitation contributes to recharge. Still moderate rainfall, which occurs more frequently, represents c. 60-90% of the total annual precipitation. The moderate events are largely under represented in the aquifer but represent the bulk of the rainfall. These results indicate that a large percentage of the precipitation is lost

during light to moderate events. The water retained in the soil after such events is likely to be lost through evapotranspiration. When runoff occurs, the water concentrates and saturates the soil in the flow lines. Here an excess of soil water occurs that cannot be retained in the soil and therefore will contribute to recharge rather than be lost by evapotranspiration. Water harvesting techniques are based on the same principle of concentrating runoff. Hence, the next chapters focused on the runoff from these systems in different sites of the study area.

Surface water in limestone and dolomite mountain ranges in semi-arid regions is rare. Therefore, water harvesting systems, ancient systems used to collect the runoff from hillslopes, can be found at regular distances to supply water points for grazing animals. The hydrological behaviour, of a range of hillslopes and small catchments, has been studied by monitoring the rainfall and runoff for such water harvesting systems. **Chapter 3** followed four water harvesting systems draining hillslope ranging from 0.4 to 6 ha and a small catchment of 21 ha during 7 years. Hydrological connectivity is overall very low, re-infiltration of runoff frequently occurs (56 events not reaching the reservoirs against 14 events with continuous runoff). The four water harvesting systems have similar vegetation but different patterns of soil surface properties. The seven year monitoring has demonstrated that these water harvesting systems collect different volumes of runoff. Runoff pathways are seldom continuous up to the outlet, as spatial patterns of soil properties are irregular and low antecedent soil moisture conditions for most storms reduce the runoff coefficients. Hence, the seasonality of precipitation and antecedent soil moisture conditions controls the connectivity of the flow into the water harvesting system. Chapter 3 stresses the need to consider the local soil moisture condition, which may change with soil properties and climatic characteristics varying in function of the altitude. The concentration of rainfall over the winter season meant that soils dry out quite slowly and that the antecedent precipitation index (API) used as a proxy of the soil moisture condition, had to be calculated over a period of 20 days (API20). Multiple

logistic regressions showed that two main factors, total precipitation and antecedent soil moisture condition, explain the runoff at the outlet of each of the four water harvesting systems. Thresholds for these variables need to be overcome before runoff reaches the outlet. These thresholds are different and depend on the size of the impluvium and the spatial arrangement of soil surface properties. The comparison between the four hillslopes reveals that thresholds are lowest for hillslopes with a short distance from the rock outcrops to the reservoirs and a low vegetation cover. The study shows that potential for water harvesting or artificial recharge can be estimated based on the 80% probability of runoff occurrence calculated using the logistic regression.

Chapter 3 showed the importance to consider the water harvesting on an event base taking into account the large spatial variability of soil surface properties and the temporal variability in precipitation and antecedent soil moisture conditions. **Chapter 4** proposes a modelling approach to evaluate the functioning and the effectiveness of three water harvesting systems. The selection of the model was limited by the data availability. Moreover, the model had to be spatially distributed given the discontinuity of the runoff (see chapter 3). The STREAM model was preferred, it is an expert based model and input parameters are easily obtained directly in the field. The STREAM model provides the hydrological network and evaluates the runoff connections. However, this model was never applied in semi-arid environment and adaptations are proposed in this chapter. In order to adapt the model to the hydrological conditions of rangelands in semi-arid climate, parameters highlighted in the previous chapter should be taken into account. Areas with the same hydrological behaviour (i.e. distribution of rock outcrop and vegetation cover) were grouped into spatial units where runoff processes are similar; five hydrologic units have been distinguished. Final infiltration capacities were attributed to these hydrological units based on values found in the literature. Decision rules governing the local climate conditions, such as antecedent soil moisture and length of the storm were proposed. The use of total storm rainfall during the period for which the intensity is higher than 5

mm h⁻¹ t_{eff} gave the best results. The prediction performances are acceptable for the three water harvesting systems with an RMSE of 13.9 m³. Given the large variability in annual runoff observed ranging from 0 to 172 m³ and the low number of events per year, the uncertainties (RMSE) are acceptable for the estimation of the effectiveness of water harvesting systems. Furthermore, the spatial patterns of soil surface characteristics are crucial for collecting runoff at the outlet of the system. In order to test the water harvesting effectiveness, the model has been applied with slight changes in very small areas within flow paths and compared with the same hillslope without any modifications. It was shown that a limited degradation of the vegetation and sealing of the soil surface can lead to an increase of annual runoff by at least by a factor two.

The use of a unique set of hydrological parameters for the three water harvesting systems on different hillslopes would imply that we can attempt the prediction of runoff from any rangeland hillslope within the same region. In **chapter 5**, the same hydrological model is used to simulate runoff in a catchment of 26 km² in order to predict the quantity its volume and its propagation distance into the stream-beds. The STREAM model was used to estimate the volume of runoff entering the stream-beds. However, new parameterisation is needed on some inputs i.e hydrological response units were based on earth observation data and rainfall data was spatially distributed. The others parameters remained unchanged. The runoff patterns were assessed and found to be comparable with patterns at the hillslope scales (Chapter 4). However, higher thresholds in the precipitation volume and antecedent soil moisture conditions were required since a return period of 6 month was found to be required to produce runoff at the outlet. Concentration of surface water occurs during moderate to heavy storms as a result of runoff from impermeable or low permeable areas. The spatial distribution of transmission losses of runoff in the stream-beds was characterised by ephemeral flow, most of the time concentrated runoff rapidly infiltrates.

The relative importance of the recharge rate induced by the runoff was estimated by comparison to other methods for the same catchment (e.g. stable

water isotopes and chloride mass balances). Discharge in the Celin spring (at the outlet of the catchment) integrates both pathways that exist for recharge in carbonated aquifers (i.e. diffuse percolation and concentrated infiltration of surface water in favourable zones such as ephemeral stream). Isotopic methods and the chloride mass balance gave a recharge rate of 4.25 hm³ per year. Whereas the mean annual infiltration was estimated at about 0.4 hm³ per year, ranging to 0.23 hm³ in a dry year to 0.61 hm³ in wet year. The mean annual contribution of recharge in the stream-beds thus amounts to about 10% of the total recharge. These results indicate that a non negligible volume of water from concentrated runoff has an impact on groundwater recharge. The infiltration by diffuse or concentrated infiltration in function of altitude shows that the main recharge zone ranges from 1800 to 1900 m a.s.l. The main factors that explain the preferential recharge in this range are i) 56% of the stream-beds surface are above this limit, ii) this area has a low vegetation cover and iii) at this altitude rainfall events are more abundant. This result is quite new to the study area where runoff is generally considered as negligible.

Recommendations for water management

The approach developed in this thesis (i.e. defining controlling factors at the hillslope scales and extrapolating the method and modelling approach to a larger area) provide a useful tool to water management at both scales. The model used in this thesis is based on a geographic information system that allows a direct visualization of the results. The precise location of the information may have several applications for different types of users such as a land owner wanting to optimize the water resource locally on his land or more broadly those responsible for management at the scale of the Sierra de Gador – Campo de Dalías.

The effectiveness of water harvesting systems has been tested at the hillslope scale. At this scale the slightest change provided that it is carried out in one of the flow paths, can result in an increase in the runoff production at the outlet. The method used in this thesis can be applied to design other water harvesting systems, to locate zones where runoff will be more easily generated and where the runoff will more likely have connectivity to the outlet.

Recharge is dominated by water from Mediterranean origin (d -excess = 13 to 16 ‰). This corresponds mainly to intensive convective storms (Vallejos et al., 1997; Vandenschrick et al., 2002). It has been estimated that extreme events represent 40% of total precipitation volume. Moderate events, mostly of Atlantic origin, are under represented in the recharge to the groundwater. Regarding to simulations at the larger scale, the maximum runoff volume was generally located in three sites easily identified in the catchment, presented in the Figure 5.2b. For the most extreme events, Celin outlet (site 1) shows the maximum runoff volume (Fig. 5.6c). The point 2 shows significant runoff quantity since it was located at the confluence of two ephemeral stream beds into the catchment and then runoff is partially or totally infiltrate into the streambeds before reaching the outlet. However, this site represents area of interest for artificial recharge and could be useful for the management of water resources. Predicted runoff quantity evaluate the potential runoff at this site ranging to 0.02 hm³ to 0.13 hm³ depending of the rainfall events (Table 5.3). For a precipitation with a return period of 6 month, in dry to moderate conditions, runoff is mainly produced upstream of the point 2 such as runoff volume represent quite the double in this point comparing to the outlet. Whereas, for a more extreme rainfall events, runoff at point 2 and runoff at the outlet is comparable. The infiltration downstream is probably less consequent in humid conditions and moreover additional runoff volume is coming from the slopes. However, the important point to notice is that on site 2 the amount of runoff collected is in the same order of magnitude or even greater and more frequent than to the outlet. However dams are already installed into the Sierra

in order to prevent from flooding and to favour the infiltration into the aquifer of water accumulated behind these systems. However, these dams are active for a rainfall of a return period over 5 years. What we proposed here are intermediate measures of functioning for return periods of about 6 month to 1 year. Installation of a reservoir in the point 2, to hold water runoff for direct use or to allow water to infiltrate more effectively can be considered. In addition, modelling the entire sierra and evaluate hotspot of runoff on the entire mountain can be a useful tool to water management to increase the water resources.

Perspectives for future research

Parameters of the model

This study shows a first estimation of recharge rates expected in zones where runoff concentrates. **Precipitation** was considered to be spatially distributed along an altitudinal gradient. Taking into account spatially distributed precipitation influences the runoff production. Rainfall events used in our simulations are mainly winter rains so that the rainfall volume decreases from the top of the Sierra to the outlet, taking into account the gradient of altitude. Convective rainfalls are generally much more localized and can produce a very different hydrological response.

Antecedent moisture condition is not entirely spatially distributed. Instead each hydrological response unit in function of the antecedent precipitation index (**API**) has different initial soil storage. However, in the case of the series of storms, patterns of soil moisture content may be present and thus the catchment can not be uniformly in the same state of antecedent moisture condition.

Using satellite imagery to map and create a simple **Hydrological response units** classification is extremely useful. Therefore, to improve the classification the method applied would require more field measurements. The

comparison between the NDVI and vegetation cover were realised for the Sierra de Gador but control points in the Celin catchment will increase the accuracy of the method. The hydrological response unit was based on the classification of the satellite image, and the stream-beds need to be more characterised. The hydrological properties of the surface and vegetations surrounding the channel will probably have an impact on the hydrological response. Moreover, length and width of the stream-beds will improve the estimates and perhaps consider the stream-beds as hydrological response units.

Furthermore, the STREAM model is based on surface processes. Infiltration into the stream bed is estimated, but subsequent percolation and aquifer recharge is not explicitly predicted. The loss of concentrated runoff in the stream beds by evapotranspiration is probably limited although the impact of the vegetations around or in the stream beds should be considered. The vegetation is adapted to such environments. While some plants adapt their physiology to reduce the growing season in order to benefit from the rare available water, others such as phreatophytes develop long-roots and can absorb water from ground supply.

Finally, parameters of the model need to be tested to give more insight to the model. The sensitivity of the model to the input parameters such as the determination of classes of hydrological response units, spatially distributed rainfall, the rainfall duration, and the spatially distributed antecedent soil moisture conditions, which describe the effect of the regional meteorological conditions, would be interesting to test.

Data to validate estimations

Good estimates are founded on close observation and detailed description of the field characteristics. Modelling results based on a limited number of events do not allow precise estimates for a management plan. Monitoring exercises have to be performed, long term recorded period is the only way to produce good future projections. Some sampling on precipitation,

surface water and from snow and groundwater were taken and give a good overview of the isotopic characteristics (Vallejos et al., 1997; Vandenschrick et al., 2002). However, the sampling was realised in a limited periods of time (few days). To have complete understanding of the stable water isotopic estimates in function of the type of precipitation and processes occurring after infiltration or surface water and interaction in the recharge system, a more complete sequential sampling is required. A research in this direction started at the Estacion Experimental de Zonas Aridas, Consejo Superior de Investigaciones Cientificas in Almeria (Spain).

Improve the knowledge of the recharge system

A complete understanding of available water resources in the Sierra de Gador and Campo de Dalias must be obtained. However, for a full knowledge of the recharge system, an aspect that was neglected in previous research is the impact of snow on the recharge rate. Snow is not uncommon during the winter months, the gradual melting saturating the soil can have a significant impact on water resources.

Applications

The model was never tested in another semi arid environment, therefore to improve it strengthen the adaptation propose in this thesis, the model need to be applied in other semi-arid catchments. The model could be used to test the influence of dams for example and could be helpful to select the best water management option. A long term perceptive, considering the direct and indirect recharge of the groundwater would be to evaluate the impact of reforestation and land use change in this area on groundwater recharge rates.

Personal considerations

Sustainability is a major concern in natural resource management. Balancing economic development, social aspect and safeguard the environment

is not an easy task especially for countries with a growing economy. The study area has faced to an extraordinary growth based on the development of agriculture in greenhouses and more recently increased tourism. The assessment of sustainable development must find a compromise between i) socio-economic development, ii) preservation of the groundwater and iii) reduction of salt intrusion.

The business as usual scenario of the ALERT decision support system indicates that the groundwater in the Andarax basin will continue to be depleted with important consequences for the environment, but particularly for maintaining economic growth and overall development of the region.

The current exploitation of the resource is clearly not sustainable and will result in the inability of the resource to meet the future demands. Efforts must be made by policy makers and end-users and combined decisions must be taken to maintain the growth of the region. An easy solution does not exist, given the complexities of the recharge system of the groundwater. However, limiting the development of greenhouses, control the growth of tourism, improve the quantitative assessment of the water balance of the aquifers, and establish threshold values for the water exploitation would be significant steps forward.

We must believe in the development of techniques which are less water consuming and more environmentally friendly, encourage the replacement of old greenhouses by new greenhouses which improve the use of water, install systems of wastewater reuse for greenhouses and open green spaces.

The question that remains is how Spain and Almeria region can remain competitive and can maintain their economies sustainably. It might be good for the future to provide other types of production.

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