

Significance of Preferential Infiltration Areas for Groundwater Recharge Rate Estimated with APLIS in the Mountain Karst Aquifer System of Sierra de las Nieves (Southern Spain)

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Abstract Researchers have been troubled with finding a reliable technique for estimating groundwater recharge in carbonate aquifers. Many studies have recognized the importance of preferential flow in karst systems. Despite this evidence, preferential infiltration has no effect on estimating recharge with a classical soil water budget. The present research aims to determine the significance of the correct location of preferential infiltration areas in estimating recharge with the APLIS method. The study was carried out in Sierra de las Nieves aquifer (Southern Spain). The effect of correctly estimating the preferential infiltration areas is studied through different levels of complexity in the geomorphological information: (i) a classical geomorphologic map with pothole databases available, (ii) a reviewed geomorphologic map, and (iii) fracture density and epikarst cartography obtained with field work and remote sensing interpretation. The obtained results provided a mean difference of more than 10 % of recharge in the whole aquifer, and up to 20 % when the pixel scale is considered at.

Keywords APLIS · Preferential infiltration · Recharge estimation · Sierra de las Nieves

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1 Introduction

Groundwater recharge is the amount of rainwater entering to the aquifer during a given period of time. However, recharge may also come from surface water sources or from the groundwater of adjacent aquifers. Recharge may be defined as a percentage of annual precipitation, and is then known as the rate of recharge or of effective infiltration. Knowledge of aquifers recharge is important because it allows identifying the water inputs or resources entering the aquifer, that is, the amount of water potentially available for sustainable human use. This knowledge is fundamental for appropriate hydrologic planning and water management.

Recharge is an issue addressed in different manuals of Hydrogeology. However, the spatial distribution of recharge is a less studied aspect, especially in the karst aquifers due to their special characteristics in regard to its hydrogeological behavior and modalities of infiltration. During the last few years, several studies have considered this important aspect with different approaches and degrees of success (Andreo et al. 2008; Andreu et al. 2011). In Andreo et al. (2008), the APLIS method developed by IGME-GHUMA (2003) was presented. APLIS evaluates the mean recharge and the spatial distribution of the carbonate aquifers, from investigations in aquifers in the South of Spain, located in different geological and climatic conditions. This method was modified and improved by Marín (2009) adding one correction factor that depends on the hydrogeological characteristics of the materials outcropping on the surface. Lately, the method has been effectively applied in several karst Spanish aquifers and Cuban aquifers. APLIS provides a way of calculating long-term spatial average recharge. It is not recommended to quantify short-term recharge because the recharge process can be influenced by several factors such as the degree of saturation of the soil and unsaturated zone or rainfall intensity.

The experience in using this method suggests that most of the input variables in APLIS are easy to calculate from available data bases or previous reports. However, a preferential infiltration factor is typically estimated based on field works or interpreting geomorphologic maps to identify zones where infiltration through exokarstic forms is predominant. Additional sources of information can also be used: topographic maps, aerial and satellite images, speleological data, spring hydrographs, tracer tests results, and hydrochemical data. It is not easy to join all this material and often databases are not exhaustive or complete. Moreover, contradictory interpretation is sometimes possible depending on the karst expert opinion.

As a part of a bigger hydrogeological research project (KARSTINV), it was necessary to estimate the recharge in the karst Sierra de las Nieves aquifer. An unexpected finding came out when it was decided to improve the preferential infiltration map with actual and more complex sources of data. Frequently, this information is difficult to translate into a preferential infiltration factor without being subjective. This work aims on investigating the effect of different kinds of information that hydrogeologists can use to develop preferential infiltration maps on the APLIS annual recharge percentage.

2 Study Area

Sierra de las Nieves is an important relief of the Málaga province (southern Spain) with outcrops of dolostones and limestones of Triassic and Jurassic age, which are permeable by fracturation and karstification. Karst features are abundant in this aquifer. The drainage of the aquifer takes place at its southern edge through several springs. Response to precipitation is very rapid such as occurs in karst aquifers with conduit flow behavior. The mean annual precipitation is 1,000 mm/year. The values of average annual temperature of the air and the evapotranspiration calculated with the method of Hargreaves are 15 °C and 980 mm/year, respectively. The aquifer is recharged by infiltration of rainwater, and, occasionally, by snow. Using the water balance method a coefficient of recharge of 55 % was found by IGME-GHUMA (2003).

3 Methodology

3.1 APLIS Method

The APLIS method allows to estimate the mean rate of annual recharge in carbonate aquifers, expressed as a percentage of precipitation, on the basis of the characteristics of these aquifers (Andreo et al. 2008) such as altitude (A), slope (P), lithology (L), preferential infiltration layers (I), soils (S), and a correction factor (F_h) that depend on the hydrogeologic characteristics of the materials outcropping on the surface (Marín 2009). Its application requires developing a map of that data, in a geographic information system. For each of these layers of information, it applies a score system to create a map of each variable. Scores range from 1 to 10, following an arithmetic progression with a step width of 1, with the aim to easily equate to aquifer recharge rates. The value 1 indicates minimal incidence of the variable in the recharge of the aquifer, whereas the value 10 expresses the maximum influence on recharge. Ranks and scores are described in Andreo et al. (2008) and Marín (2009).

The following expression is used to estimate the recharge rate (Marín 2009):

$$R = [(A + P + 3 \cdot L + 2 \cdot I + S) / 0.9] F_h \quad (1)$$

The weight of each variable in the above expression is intended to represent its importance in determining the recharge rate, in accordance with the results obtained from the prior analysis of the variables that influence recharge. By dividing by 0.9, recharge rates are obtained that range from a minimum of 8.88 % to a maximum of 88.88 % of the rainfall onto the surface of the aquifer.

The layers of information corresponding to each variable are taken from different sources. The digital elevation model map, scale 1:10,000, was used for the mapping of altitude and slope. The geological map was grouped in lithological sets of similar hydrogeological characteristics taking into account the geomorphologic forms. The discretization used for all the maps in this work is of 5×5 m.

3.2 Preferential Infiltration

The APLIS method was already applied in Sierra de las Nieves (IGME-GHUMA 2003), obtaining an annual recharge rate of 54 %. In this previous work, preferential infiltration areas were assessed limiting the sectors with karst forms of favorable infiltration and slopes of less than 8 %. Geomorphological maps were also consulted for this task. In this previous study, a 12 % of the total aquifer area was assigned to have preferential infiltration distributed in two zones (Fig. 1): the Nava paleopolje and the port of Los Pilonos, with low slope and many dolines and simes.

For the present study, this information has been significantly improved by satellite images, interpretation of aerial images and exhaustive field work. The evaluation of this material resulted in different levels of complexity and types of geomorphologic indicators. These maps had to be transformed into *I* scores and three different preferential infiltration maps were constructed depending on the data used (Fig. 1): *Case 1*. Geomorphological map and cells that include a polje (closed depression covering a considerable surface area) as well as the ones containing at least one significant pothole are included. Finally areas with a slope less than the 3 % are added. *Case 2*. An improved geomorphologic map of Sierra de las Nieves aquifer has been developed from exhaustive terrain work and aerial photo interpretation. In this case it was decided to create two different ranges of scores to obtain the *I* map. *Case 2a*, with just 1 (scarce exokarstic forms) or 10 (abundant exokarstic forms) values as in Andreo et al. (2008), resulting in the map shown in Fig. 1. And *Case 2b*, a new proposed score system to improve the APLIS method of grading the scores between 1 and 10 with the ranking shown in Table 1. *Case 3*. Fracture density and epikarst cartography from field work and remote sensing interpretation give the preferential infiltration areas.

4 Results and Discussion

Figure 2 shows the calculation results for each of the studied cases. The results shown are based on the application of APLIS Eq. (1) applying each of the four different maps shown in Fig. 1, and the rest of the variables remain the same. Each of the figures displays the annual recharge rate for each of the combined maps. All the figures show different values reflecting the differences of areas of preferential

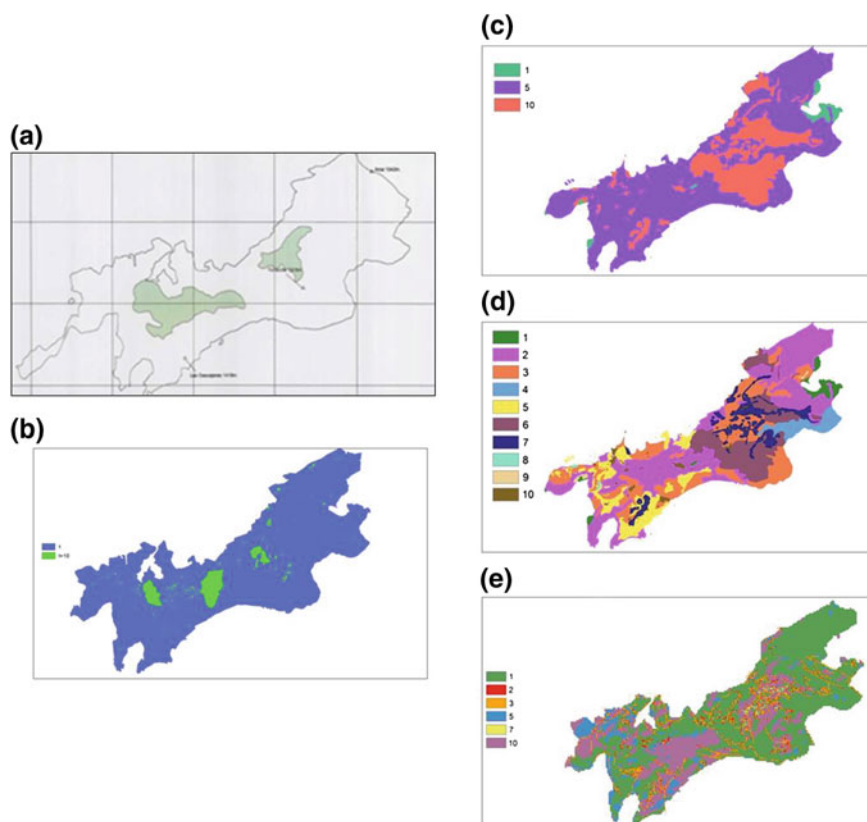


Fig. 1 Preferential infiltration areas used in the different studied cases. **a** I areas from IGME-GHUMA (2003). **b** I areas Case 1. **c** I areas Case 2a. **d** I areas Case 2b. **e** I areas Case 3

Table 1 Proposal of new *I* scores for preferential infiltration variable in APLIS

Exokarst form	<i>I</i> score
Doline	10
Polje	10
Doline with crops	9
Karst flatted	8
Karren field nude with high development and fractures	7
Karren field nude with high development and microformes	6
Karren field low covered and fractured	6
Quarry	5
Karren field nude with low development	5
Karren field low covered	4
Karren field covered and fractured	3
Karren field covered	2

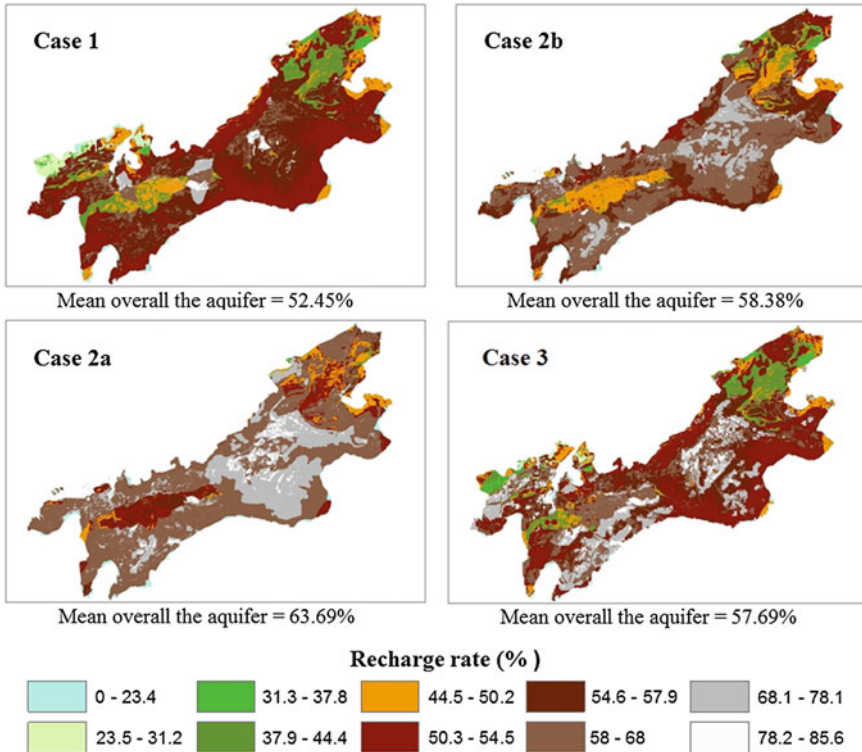


Fig. 2 Recharge rates values for the four studied cases

infiltration. *Case 1* is the one that results in the smallest values (mean of 52.45 %) and *Case 2a* in the highest (mean of 63.69 %). *Cases 2b* and *3* have very similar mean values (58.38 and 57.69 %, respectively). On the other hand *Case 2b* has less dispersed values (10.71 % of standard deviation) than *Case 3* (12.41 % of standard deviation).

The minimum recharge value (i.e., $I = 1$ in all the aquifer) is computed for comparison purposes between the studied cases. This minimum value is subtracted from the four resulted maps. Mean values of these differences are 0.9 for *Case 1*, 11.3 for *Case 2a*, 6.0 for *Case 2b* and 5.8 for *Case 3*. These numbers, again, show that *Cases 2b* and *3* are very similar. Figure 3 reflects the spatial distribution of differences and the variations among all the methods. *Cases 1, 2a* and *3* tend to concentrate high preferential infiltration rate in some areas, depending on the expert interpretation and the data available. *Cases 1* and *3* give very low preferential infiltration rates in the rest of the aquifer, while *Case 2a* gives a medium value. For *Case 2b*, a new score table for preferential infiltration has given, with a more graduate recharge rate. New I scores are reflected in the results and in the

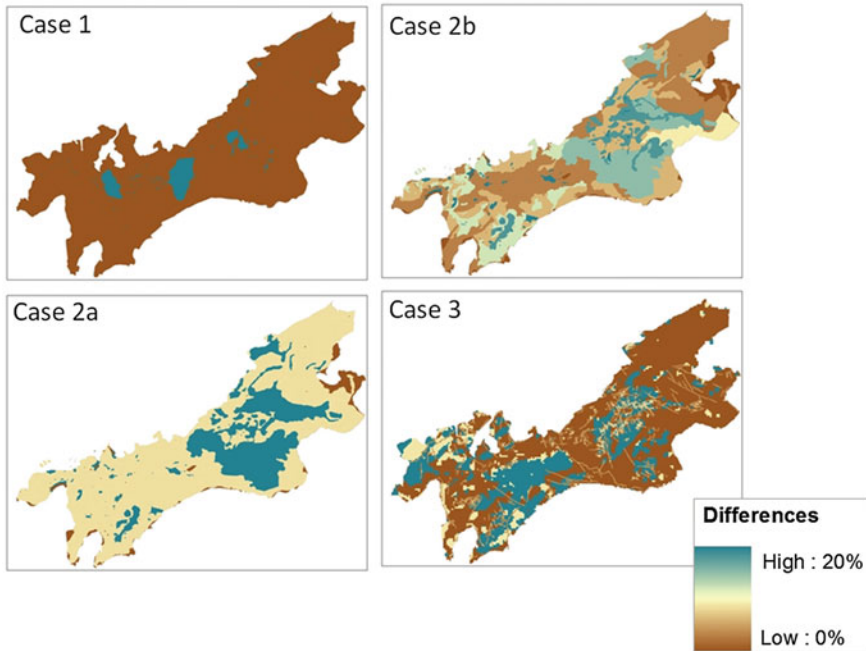


Fig. 3 Spatial distribution of differences of recharge rate values (%) for the four studied cases and the map resulted from using $I = 1$ all over the aquifer

differences with the map of $I = 1$ in the whole aquifer (Fig. 3). This proposal results congruent with the ones computed in IGME-GHUMA (2003) and appear to be more realistic following the recharge process in karst aquifers.

5 Conclusions

The study was able to evaluate differences introduced by the preferential infiltration factor in the recharge rate estimation. The results obtained provided a mean difference of more than 10 % of recharge in the whole aquifer, arriving to differences of 20 % when the pixel scale is looked at. The study of karst and epikarst has allowed developing a realistic estimation of the actual aquifer recharge. The proposal of using a new score for preferential infiltration gives congruent values introducing an improvement in the APLIS method.

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