Professur für Hydrologie
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Improved Assessment of Drinking Water Security in a Mediterranean Karst Region
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Andalusia, Spain

Masterarbeit unter Leitung von Dr. Andreas Hartmann
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Referent: Dr. Andreas Hartmann
Korreferent: PD Dr. Jens Lange

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Summary

Karst water resources present an important source for human water supply. In Andalusia in southern Spain the groundwater resources of the karst aquifers in the Betic Cordillera are especially important for securing water supply during the regular drought periods. In consequence of climate change the relevance of groundwater resources will increase. Moreover the Mediterranean region is projected to be particularly influenced by the effects of climate change. Hence it is necessary to establish a sustainable water management that requires tools to estimate groundwater recharge. This is the amount of the precipitation that percolates down to the water table and is added to the groundwater.

APLIS represents a method which has already been widely used in the Mediterranean and in further aquifers worldwide. It is a GIS based tool to estimate spatially distributed mean annual recharge in carbonate aquifers expressed as a percentage of annual precipitation. However, it does not include the temporal distribution of precipitation and evapotranspiration which has a strong influence on the process of recharge generation. It needs to be considered to provide more realistic results for groundwater recharge. In this study the APLIS method was extended with a simple soil water balance routine to enable time dynamic recharge estimations in combination with the spatially distributed recharge calculations of APLIS.

The new method was applied in the two karst aquifers Villanueva del Rosario and Sierra Blanquilla near Malaga in Andalusia, Southern Spain. It was evaluated with spring discharge data, of the two karst systems. Aside from the application to measured meteorological data it was also applied to climate scenario data of five different global climate models. These were divided into three time periods representing present (1989-2009), future (2039-2059), and remote future (2079-2099). In each case the driest, wettest, and average year over the time period was analyzed.

The evaluation suggested a successful implementation of the method for the Villanueva del Rosario catchment. For the Sierra Blanquilla study site not enough data were available to show with certainty the transferability to another catchment. However, the results indicated that it is possible. The strong influence of the temporal rainfall

pattern became evident in the results. Whereas APLIS is underestimating recharge in wet years and overestimating in dry years, the new method results in values much closer to the observed discharge rates. It could be shown that high-intensity rainfall events generated most recharge. It is therefore relevant to include the temporal rainfall pattern to capture those rainfall events. Furthermore, the findings prove a linear relationship between the amount of precipitation and recharge, and a non-linear relation between precipitation and recharge rate. The results for the climate scenario data suggest a decrease in future recharge for the average years. For the wet years the results were not entirely clear, since one model simulated an increase in recharge. The range of values in the results for the climate data emphasized the uncertainty that is involved with these results.
Summarized this thesis shows highly promising results and suggests a simple tool for recharge estimations for practical use in water management.

Keywords: Groundwater recharge, Karst aquifer, Mediterranean, Spain, climate change, spatio-temporal recharge estimation, APLIS, soil water balance routine

Zusammenfassung

Wasserressourcen aus Karstaquiferen stellen eine bedeutende Quelle für die Wasserversorgung dar. In Andalusien in Südspanien sind die Grundwasserressourcen der Karstaquifere der Betic Cordillera besonders während der regelmäßig wiederkehrenden Trockenperioden wichtig für die Wasserversorgung der lokalen Bevölkerung. In Folge des Klimawandels wird die Bedeutung von Grundwasser für die Wasserversorgung weiter zu nehmen. Weiterhin wird vorhergesagt, dass der Mittelmeerraum von den Auswirkungen des Klimawandels besonders betroffen sein wird. Es ist also nötig ein nachhaltiges Wassermanagement durchzuführen. Dafür werden Werkzeuge benötigt mit deren Hilfe die Menge der Grundwasserneubildung berechnet werden kann. Grundwasserneubildung ist der Anteil des Niederschlags, der durch den Boden bis zum Grundwasser durchsickert und zu diesem hinzugefügt wird.

Die APLIS Methode wurde bereits mehrfach im mediterranen Raum, sowie weltweit in verschiedenen Aquiferen eingesetzt. Es ist eine GIS basierte Methode zur Berechnung der räumlich verteilten mittleren jährlichen Grundwasserneubildung in Karstaquiferen. Die Neubildung wird als prozentualer Anteil am jährlichen Niederschlag angegeben. Die Methode bezieht nicht die zeitliche Verteilung von Niederschlag und Evapotranspiration ein, obwohl diese einen großen Einfluss auf die Entstehung der Grundwasserneubildung hat. Folglich muss das zeitliche Muster in den Berechnungen berücksichtigt werden, um realistischere Ergebnisse für die Neubildung zu erzielen. In dieser Masterarbeit wurde die APLIS Methode durch eine einfache Bodenwasserbilanz-Routine erweitert, um eine zeitlich dynamische Berechnung der Grundwasserneubildung zu ermöglichen.
Die neue Methode wurde in den zwei Karstaquiferen Villanueva del Rosario und Sierra Blanquilla in der Nähe von Málaga in Andalusien in Südspanien angewendet. Die Ergebnisse wurden mit Abflussdaten von Quellen der Aquifere evaluiert. Neben der Anwendung auf gemessene meteorologische Daten, wurde die Methode auch auf Daten von fünf globalen Klimaszenario-Modellen angewendet. Die Daten der Klimamodelle wurden in drei Abschnitte eingeteilt: Gegenwart (1989-2009), Zukunft (2039-2059) und entfernte Zukunft (2079-2099). Für jeden Zeitabschnitt wurde das trockenste und

feuchteste Jahr untersucht, sowie der jährliche Durchschnitt über den Abschnitt.
Die Ergebnisse der Evaluation zeigten eine erfolgreiche Umsetzung der Methode im Villanueva del Rosario Gebiet. Für das Sierra Blanquilla Gebiet waren nicht genug Daten vorhanden um mit Sicherheit sagen zu können, dass die Methode auf andere Gebiete übertragbar ist. Die Ergebnisse veranlassten jedoch zu der Annahme, dass dies möglich ist. In den Ergebnissen wurde der starke Einfluss des zeitlichen Niederschlagsmusters deutlich. Während APLIS die Neubildung in feuchten Jahren unterschätzt und in trockenen Jahren überschätzt, waren die Ergebnisse der neuen Methode wesentlich näher an den Ergebnissen der gemessenen Abflussraten. Es konnte gezeigt werden, dass durch Niederschlagsereignisse mit hohen Intensitäten die meiste Neubildung generiert wurde. Somit wurde auch deutlich wie wichtig es ist das zeitliche Muster der Niederschlagsverteilung zu beachten, um solche Ereignisse mit hohen Intensitäten zu erfassen. Weiterhin wurde eine lineare Beziehung zwischen der Neubildungs- und Niederschlagsmenge gefunden, sowie eine nicht-lineare Beziehung zwischen der Niederschlagsmenge und der Neubildungsrate. Die Ergebnisse für die Klimaszenario-Daten zeigten eine Abnahme der Grundwasserneubildung in der Zukunft für die jährlichen Mittelwerte. Für die feuchten Jahre waren die Ergebnisse nicht ganz eindeutig, da ein Modell eine Zunahme der Neubildung simulierte. Die Spannbreite der Ergebnisse für die Daten der Klimamodelle hat außerdem die Unsicherheit betont, die mit Klimaszenario-Daten und deren Ergebnissen verbunden ist.
Zusammengefasst konnte diese Arbeit vielversprechende Ergebnisse erzeugen und eine Methode vorstellen, die ein simples Werkzeug für die Berechnung der Grundwasserneubildung zur Anwendung in Wassermanagement Fragen darstellt.

Stichworte: Grundwasserneubildung, Karstaquifer, Mittelmeerraum, Spanien, Klimawandel, räumlich-zeitlich verteilte Neubildungsberechnung, APLIS, Bodenwasserbilanz-Routine

1 Background

In (semi-)arid regions groundwater is the most important source of water, due to sparsely available and unreliable surface water resources (Scanlon *et al.*, 2006). Groundwater is more reliable and safer, because a more constant use of the water is ensured. The use of surface water is more influenced and thus restricted by flow variations e.g. due to droughts. Additionally the impact of anthropogenic pollution is greater on surface water than on groundwater (Portmann *et al.*, 2013). Karst water resources in particular have always been an important source for human water supply. Still today, many cities and rural populations depend on water supplies from karst aquifers. Large areas of the world's ice-free continental area are underlain by karst systems which developed on carbonate rocks. Around $20-25\,\%$ of the global population is partially or entirely dependent on the groundwater obtained from those karst systems (Ford & Williams, 2007). In Europe $35\,\%$ of the land surface is covered by carbonate rock outcrops of which large parts are karstified (Fig. 1.1). In fact, karst aquifers should be considered as the main groundwater resource in Europe and especially in Mediterranean countries, since they are of great importance in the water supply. In Spain karst groundwater accounts for $12.5\,\%$ of the total water supply (COST, 1995). Particularly in the long drought periods the groundwater of the Betic Cordillera in southern Spain is an essential source to secure water supply (Martos-Rosillo *et al.*, 2015).

However, climate change projections forecast increasing temperature, decreasing precipitation, and increased occurrence of extreme events for the Mediterranean region. At the same time the water demand for agriculture and tourism in this region is already increasing today (Treidel *et al.*, 2011). Thus, water stress in the Mediterranean will increase due to climate change causing a decrease in water resources, and due to the increased water demand for economic growth and urban expansion (García-Ruiz *et al.*, 2011). Additionally, the pressure is likely to increase particularly on groundwater resources. This is because climate change is likely to further decrease surface water reliability due to enhanced variability of precipitation and river flow (Kundzewicz

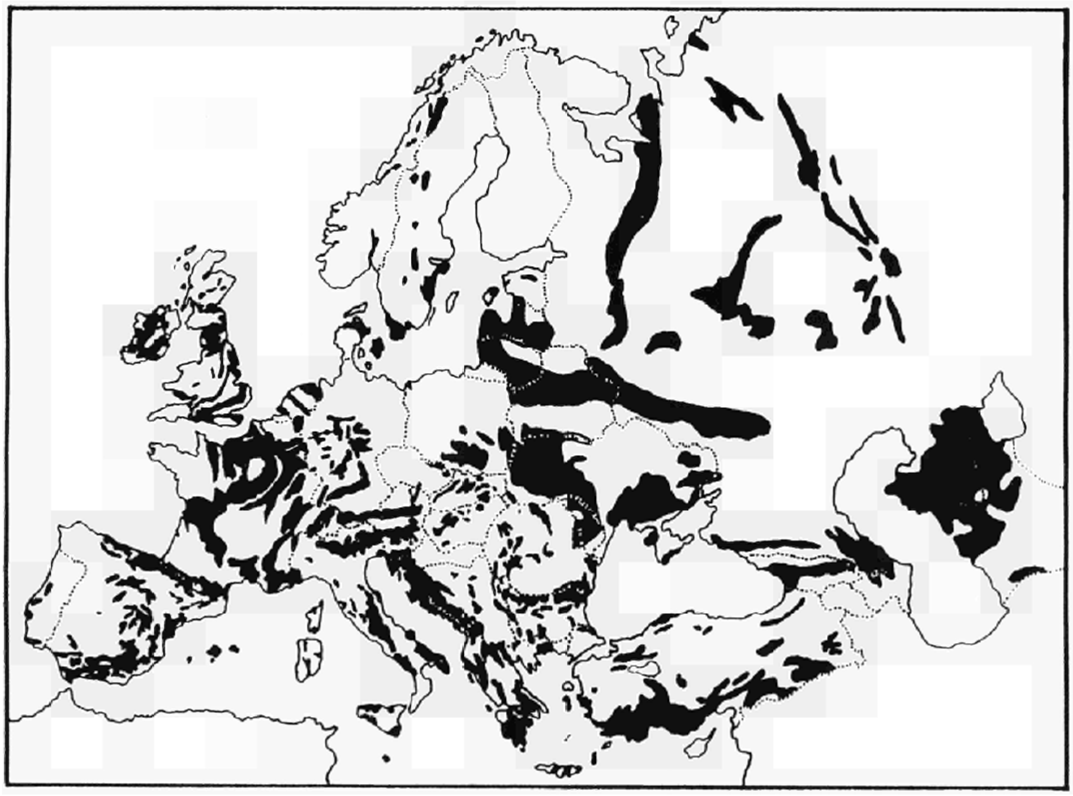

Figure 1.1: Carbonate outcrops in Europe (black). Karst features are present in most of them (COST, 1995).

& Döll, 2009). Furthermore, the Mediterranean region is located between the arid climate of North Africa and the temperate and rainy climate of central Europe. It is influenced by interactions between processes of mid-latitude and tropical regions. These characteristics effect that relatively minor modifications of the general global climate circulation can have a major effect on the Mediterranean climate. This makes the Mediterranean region potentially vulnerable to climate change, and climate model investigations show that the Mediterranean might be indeed particularly vulnerable to future global changes (Giorgi & Lionello, 2008).The great importance of karst water resources for human water supply and the projected climate change impacts, together with an already significant increase in groundwater depletion in the last decades (Wada *et al.*, 2010) clarify the need for further investigations into karst groundwater research. However, karst represents a complex medium with several special features which have to be kept in mind when investigating karst systems.

1.1 Short Introduction to Karst Hydrogeology

The term karst describes a special style of landscape that contains caves and vast underground water systems, and develops on particularly soluble rocks. The typical parent material is carbonate rock which contains more than 50 % carbonate minerals. The two major types of carbonate minerals are limestone (composed of calcite or aragonite, $CaCO_3$) and dolostone or dolomite (composed of dolomite, $CaMg(CO_3)_2$)) (e.g. Ford & Williams, 2007). Karst can also develop on gypsum or halite. However, karst systems from these rocks are not relevant for water resource management. The carbonate rocks get dissolved by carbon dioxide (CO_2) which is delivered by rain percolating through the soil, accumulating more CO_2 due to vegetation and microbial processes and reaching the underlying bedrock that consists of carbonate rocks. The process of dissolution is influenced by lithological factors, i.e. chemical and mineralogical purity of the rock as well as physiochemical factors, namely temperature and CO_2 partial pressure. In consequence of these intense water-rock interactions, karst landscape and aquifers develop over thousands of years resulting in typical surface and subsurface structures, such as karren, dolines, swallow holes, caves, dry valles, poljes, and large karst springs (Hartmann *et al.*, 2014a).

A karst system is a highly heterogeneous system (Fig. 1.2) which is characterized by a duality of (Goldscheider & Drew, 2007):

- recharge: a distinction is made between recharge originating from the karst area itself (autogenic) and recharge coming from adjacent non-karstic areas (allogenic).
- infiltration: water is infiltrating via swallow holes and dolines (point infiltration) and diffusely into fissures in the rock (diffuse infiltration). Allogenic recharge often infiltrates via swallow holes whereas autogenic recharge is more diffusive.
- porosity/flow: Two or three different types of porosity can be distinguished: intergranular pores and fractures (called the matrix), and conduits. Conduits develop due to karstification processes and range from cm-wide solutionally enlarged fractures to huge caves. There are high flow velocities in the conduits with often turbulent flow and much lower flow velocities in the matrix.

Significant water storage may occur in the matrix and in other parts like the epikarst, which is the uppermost zone of exposed karst rock, but only limited in the conduits (Goldscheider & Drew, 2007).

The conduits in karst aquifers present the big difference to other aquifers containing only intergranular pores and/or fractures and need to be considered by applying certain examination methods. For instance tracer tests are more appropriate to determine flow direction and velocity, than water-level measurements in wells or piezometers. Another point is the different conductivity in conduits and in the matrix which needs to be considered in numerical models by high- and low-conductivity elements. Furthermore, karst systems respond very quickly and intense to hydrological events. This means the water table may rise rapidly after a storm rainfall or snowmelt, the discharge can also vary severely within a short time interval. Another point to keep in mind when examining karst systems is the temporal evolution of such systems which might lead to unexpected groundwater flow paths and drainage outlet points. This is because karst aquifers are not unchanging, but they are altering through dissolution processes (Goldscheider & Drew, 2007). Another important characteristic of karst systems is that the absence of karst landforms on the surface does not mean that there is no karstic groundwater system (Hartmann *et al.*, 2014a).

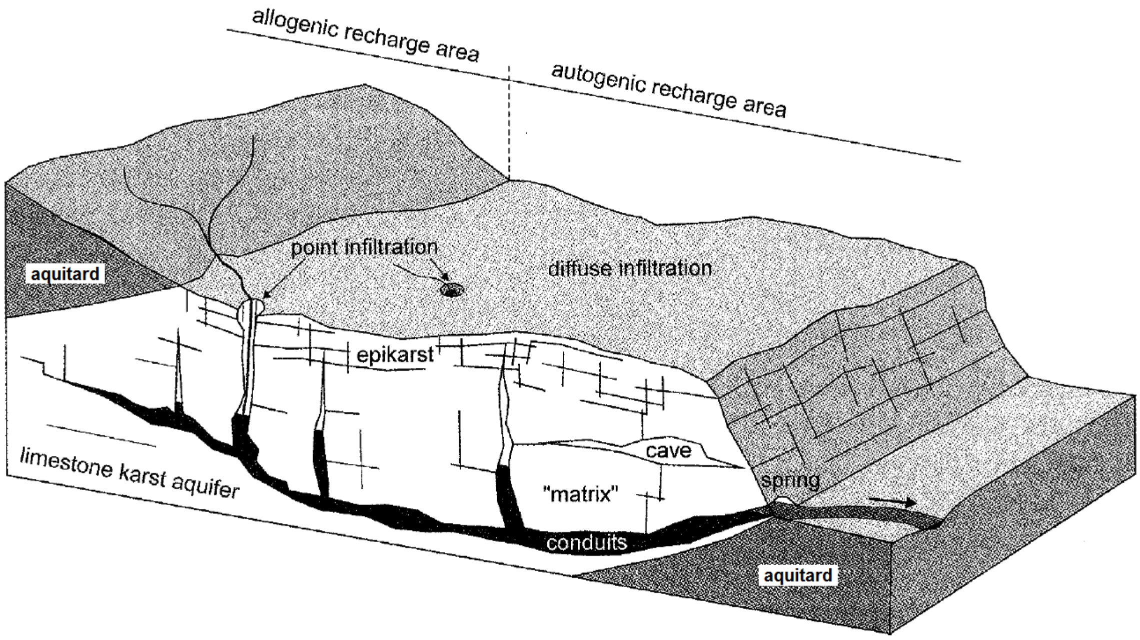

Figure 1.2: Scheme of a heterogeneous karst system with its dualities in recharge, infiltration and porosity (Goldscheider & Drew, 2007, modified).

Further information about karst hydrogeology can be found e.g. in Ford & Williams (2007) and Goldscheider & Drew (2007). The first book provides detailed information on the formation of karst and its landscapes, the latter on available examination methods and techniques.

1.2 Estimation of Groundwater Recharge

1.2.1 Definition of Groundwater Recharge

Groundwater recharge is an important variable when investigating groundwater resources. Recharge can occur naturally from precipitation, rivers and lakes or artificially e.g. from irrigation. It is generally defined as the amount of water percolating downward until it reaches the water table, where it is added to the groundwater reservoir. A distinction is made between potential and actual recharge. Potential recharge describes the amount of water from the soil zone, which is potentially available for recharge but can also be lost, e.g. due to a high water table when the potential recharge water cannot reach the groundwater and becomes runoff. Actual recharge is the water that actually reaches the water table and is added to the groundwater. Two mechanisms of recharge can be defined: direct or diffuse recharge by percolation of precipitation through the unsaturated zone as excess of soil moisture deficits and evapotranspiration. Secondly, indirect recharge from percolation of runoff accumulating in joints and ponding in low-laying areas and lakes, or through beds of surface watercourses. The part of indirect recharge that results from surface concentration of water without well-defined channels is also called localized recharge (Lerner *et al.*, 1990, Fig. 1.3).

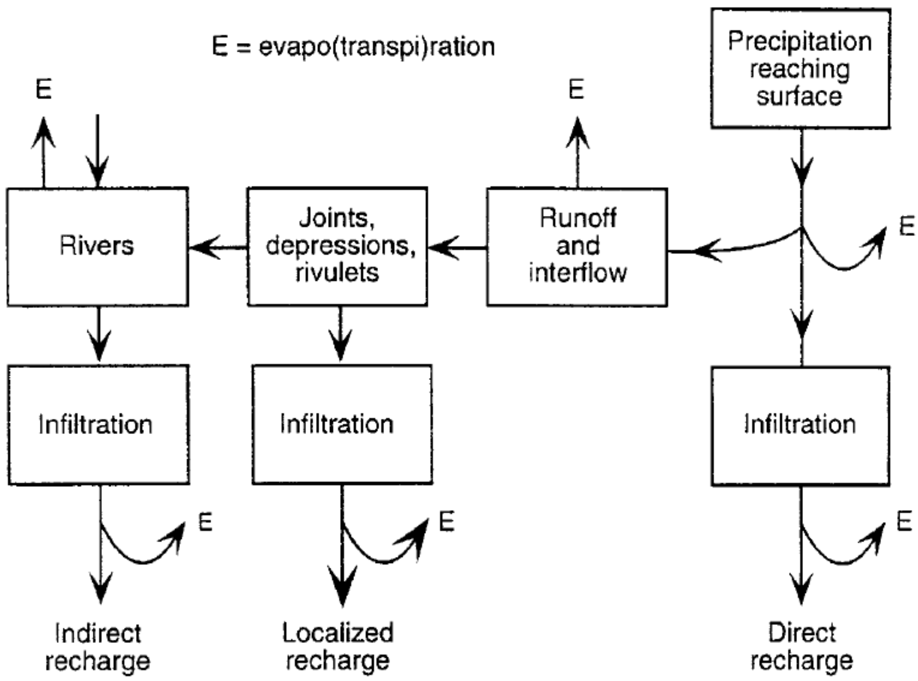

Figure 1.3: Different mechanisms of recharge in a (semi-)arid area (Lerner, 1997 in de Vries & Simmers, 2002).

1.2.2 Modeling of Groundwater Recharge

Knowledge about the correct amount of groundwater recharge and with that about the amount of water available for human use is essential for a sustainable groundwater management (e.g. Döll & Fiedler, 2008; Guardiola-Albert *et al.*, 2015). However, there are also other views, e.g. Bredehoeft (2002) argues that one can equate the amount of recharge with the amount of sustainable available water although this is a widespread misconception in groundwater hydrology. He states that the dynamic processes of an aquifer system and the response dynamics to system development need to be investigated to understand how a steady state of the system, and thus a sustainable development can be reached.

In the past, many studies on groundwater recharge and its different quantification approaches have been carried out in the past. Most of the methods to estimate recharge are intended to be used in detrital aquifers, and do not consider the special hydrogeological characteristics, such as the heterogeneous porosity and permeability of karst aquifers. In general, the methods to estimate recharge in carbonate aquifers are adapted and derived from those used for detrital aquifers (Andreo *et al.*, 2008). Besides the unusual heterogeneity of porosity and permeability of karst medium it is also the high inter-annual variability of rainfall with long dry periods and short wet periods which make accurate recharge estimations in the Mediterranean challenging (Guardiola-Albert *et al.*, 2014). Scanlon *et al.* (2002) investigated in detail the different techniques for quantifying recharge and presented an approach for choosing the appropriate technique. Generally the approaches based on surface water or unsaturated zone water provide estimates for potential recharge while techniques based on groundwater data provide estimates on actual recharge. Different techniques for recharge estimation include using lysimeters, Darcian approaches, tracer techniques, water balance methods, and numerical modeling. Challenges in estimating recharge like the highly variable behavior of recharge particularly in (semi-)arid regions are described in de Vries & Simmers (2002). Hartmann *et al.* (2014a) reviewed hydrologic modeling approaches for karst water resources and discussed methods to improve predictions for karst water resources.

On a global scale Döll & Fiedler (2008) estimated diffuse groundwater recharge using the WaterGAP Global Hydrology Model. For arid and semi-arid regions the model was modified based on long-term average recharge estimations in these regions, it enabled thus an unbiased estimation of groundwater recharge for (semi-)arid areas. Scanlon *et al.* (2006) synthesized recharge estimates for (semi-)arid regions worldwide to evaluate recharge rates, and to investigate impacts of climate and land use/land cover change on recharge. Andreo *et al.* (2008) stated that recharge assessment over large areas and its spatial distribution is a very important part in establishing a sustainable groundwater management, especially for regions where groundwater is the only available fresh water source. They developed the APLIS method, which will be further analyzed in this thesis, using aquifers in southern Spain. The GIS (Geographic Information System) based approach estimates the mean annual recharge in carbonate aquifers, expressed as a percentage of annual precipitation, based on the variables altitude, slope, lithology, infiltration landforms, and soil type. It does not include temporal variability of meteorological data and is intended to estimate long-term spatial average recharge. It is not recommended for short-term recharge calculations, because it does not consider the temporal variability of physical processes, like the degree of saturation of the soil and unsaturated zone or the intensity of rainfall (Guardiola-Albert *et al.*, 2014, 2015). However, it has already been successfully applied in several Spanish karst aquifers with different climatic and geologic conditions (Andreo *et al.*, 2008; Martos-Rosillo *et al.*, 2013). Moreover, further applications of the APLIS method in karst aquifers have been carried out worldwide by Espinoza *et al.* (2015) in Peru, Farfán *et al.* (2010) in Cuba, Gerner *et al.* (2012) in Oman and Zagana *et al.* (2011) in Greece. Martos-Rosillo *et al.* (2015) summarized the results of different recharge estimations for 51 carbonate aquifers in the Betic Cordillera including all APLIS applications in this region. Apart from these diverse applications, the method has also been improved. Marín (2009) further developed the APLIS method and proposed some modifications. Besides, including additional slope classes and refining the infiltration parameter by a new factor, a correction coefficient of recharge was introduced (Chap. 3.3.1). Guardiola-Albert *et al.* (2015) described a possibility to improve the APLIS method also by further refining the parameter of infiltration landforms through involvement of satellite images, field work, and aerial images.

Radulovic *et al.* (2012) developed a similar approach to APLIS which calculates the spatial distribution of recharge in Montenegrin karst aquifers. And also Allocca *et al.* (2014) used a GIS-based approach to calculate spatial annual mean recharge for karst aquifers in southern Italy using geomorphological, land use, and soil cover information as well as mean annual precipitation. A range of other studies have been conducted in Spain.

Alcalá & Custodio (2014) evaluated the spatial annual average aquifer recharge in continental Spain using the atmospheric chloride mass balance. Andreu *et al.* (2011) reviewed different approaches quantifying recharge and spatial variability using satellite-based modeling and tracer techniques for the quantification of potential recharge and a lumped model based on water table fluctuations for the estimations of actual recharge for carbonate aquifers in SE Spain. Martínez-Santos & Andreu (2010) applied a lumped and distributed model to quantify recharge in a karst aquifer in SE Spain which is subject to extensive exploitation. As with Hartmann *et al.* (2014b) their results demonstrated a nonlinear relationship of rainfall and recharge rates. The recharge rate seemed to increase exponentially with the amount of precipitation.

Martos-Rosillo *et al.* (2013) applied four different methods to estimate recharge in semi-arid carbonate aquifers under intensive use in southern Spain. This included application of the chloride mass balance, daily soil water balance, the APLIS method, and ERAS, a method to estimate recharge in overexploited aquifers. Also Guardiola-Albert *et al.* (2014) applied different methods to analyze recharge in a karst system in the Betic Cordillera during a wet period when the highest amount of recharge is generated. Consequently different recharge rates compared to historical means were the results of their study. However, they emphasized that this fact is often not considered in investigations. This implicates that average recharge values of long study periods are used in hydrogeological studies with the risk of serious underestimation of recharge. In their study they applied the soil water and chloride mass balance method and compared different models. This included the Visual Balan method, a lumped model which calculates daily water balances in the soil, unsaturated zone and aquifer (Samper *et al.*, 1999). Another method was the ZOODRM model for distributed recharge estimations (Mansour & Hughes, 2004). Moreover, they also applied the APLIS approach and a method for spatio-temporal recharge estimations from Pardo-Igúzquiza *et al.* (2012). They developed an approach to calculate daily spatially distributed recharge for aquifers in mountainous karst terrains using a water balance. They specifically concentrated on the consideration of the spatio-temporal variability of recharge and the characteristics of climate in Mediterranean mountainous karst terrains. There rainfall and temperature usually correlate with orography; and rainfall and evapotranspiration can have great variations over space and time. Considering the variability through daily time steps is thus an important aspect.

Also Lerner *et al.* (1990) explained that even average values of recharge over longer periods should be obtained by summing up values of shorter time intervals. The reason is the non-linearity in recharge processes which can lead to wrong estimations when calculating recharge for the entire period at once. For instance when using soil moisture balance models for recharge estimations in (semi-)arid environments, usually no recharge is detected on a monthly scale. When data is examined on a daily or event scale, recharge becomes visible. This is the effect which was also reflected in the results of Guardiola-Albert *et al.* (2014). The problem of estimating recharge with the water balance method is that recharge is usually set equal to the residual of the balance, whilst the other parameters like rainfall and evapotranspiration are measured or estimated. Consequently, the accuracy of the recharge estimates are dependent on the accuracy of the measured parameters. This is a problem if the amount of recharge is small, compared to the other parameters, especially evapotranspiration. Small errors in the values of these variables will lead to highly inaccurate recharge estimates. Yet, if the water balance is calculated on a daily basis, even in arid regions the precipitation can greatly exceed evapotranspiration on some days and the uncertainties in recharge estimations can be constrained (Scanlon *et al.*, 2002).

Thus, besides the spatial pattern of recharge it is important to quantify the temporal variability of recharge, and to make sure the temporal distribution of rainfall has been considered. As Ries *et al.* (2015) found out that the temporal rainfall pattern has great influence on event and seasonal recharge events. Like de Vries & Simmers (2002) their results suggested that recharge is greatest in semiarid regions when high intensity rainfall events occur. In the case of long-time average time series of precipitation, high-intensity rainfall events are often smoothed out although they are producing the highest recharge amounts (Scanlon *et al.*, 2002).

Hence, for reliable recharge estimations and thus sustainable water management it is essential to incorporate the temporal rainfall and evapotranspiration distribution into recharge estimations methods.

1.2.3 Estimation of Future Change in Recharge

As described in the introduction, the Mediterranean region and its groundwater resources are likely to be influenced by climate change. Therefore another important part in the estimation of groundwater recharge is the development of recharge under changing climatic conditions.

Portmann *et al.* (2013) investigated the effect of different emission scenarios on renewable groundwater resources. They applied climate data of the same five climate models, which will be used in this thesis, on the global hydrological model WaterGAP. Decreases in groundwater recharge of more than 30 % could be observed especially for (semi-)arid regions for all climate models. However, several uncertainties need to be considered. For instance land use change and recharge from surface water bodies were not considered in the recharge calculations.
Moreover, different studies about the combination of hydrological models and climate scenario data specifically for karst systems have been conducted as well. Loáiciga *et al.* (2000) studied the impacts of climate change on the Edwards Balcones Fault Zone karst aquifer in Texas, one of the largest aquifers in the United States. They concluded that the amount of pumping needs to be adjusted in order to compensate a decrease in groundwater recharge due to climate change. Also Brouyére *et al.* (2004) found a decrease in groundwater levels considering different climatic conditions. They studied the effect of climate change on a chalky aquifer in Belgium. The impact of a changing climate on the flow of karst springs in a semi-arid region in China was investigated by Hao *et al.* (2006). They also found a decrease in spring discharge following the reduced precipitation in consequence of climate change. The reduction due to human influence was of secondary importance. Hartmann *et al.* (2012) determined climate change impacts on the water availability of a large karst spring in the Eastern Mediterranean. They applied five different hydrological models and different climate projections. For the remote future, their results suggested a decrease of 15 to 30 % in water availability.

2 Problem Statement & Objectives

As stated above the APLIS approach represents a well applied and tested method with reliable results for estimating recharge rates in carbonate aquifers. A method which is fully established and thus enhancement of the method is likely to be used in addressing water management questions. However, APLIS is only capable of estimating long-term average recharge. To provide more realistic results the method needs to consider temporal variations of physical processes like rainfall in the model calculations (Guardiola-Albert *et al.*, 2014).

Hence, the objective of the master thesis is to further enhance the APLIS model by enabling time dynamic recharge estimations. It is applied in two karst aquifers in southern Spain using measured meteorological data as well as data from climate change projections. Together with the research group for hydrogeology of the University of Malaga, Spain (CEHIUMA) Hartmann *et al.* (2014b) showed that combining the spatially distributed APLIS method with the process-based karst model VarKarst provides temporally distributed information about recharge. However, the combined model needed spring discharge and hydrochemical data for calibration and the combination of the two methods was not user-friendly because it required ArcGIS, as well as Matlab programming skills. The current approach also works with the linkage of spatially and temporally variable recharge modeling methods but retains the GIS based approach of APLIS and further develops the method by introducing a soil water routine. It is intended to be preferably simple without the need for calibration, and it is based on publicly available data which can be acquired for large areas. This enables an implementation of the enhanced APLIS model on further catchments and on a larger scale, e.g. for entire Andalusia.

The main research questions of this thesis are:

1. Is it possible to integrate the temporal variability of precipitation and evapotranspiration in recharge estimations in a simple way under present data availability?
2. Is it possible to transfer the new simple method to further catchments in Andalusia?
3. What are the consequences of the consideration of temporal variability of meteorological data on the estimated recharge?
4. Can this simple method be used to assess future groundwater recharge?

3 Methodology

Firstly, the two study sites Villanueva del Rosario and Sierra Blanquilla are described. They are both located in the Betic Cordillera, an Alpine range located in southern Spain (MARTOS-ROSILLO *et al.*, 2015, Fig. 3.1). Subsequently, available data sets are explained followed by a description of the models. The time dynamic recharge modeling was done by an extension of the existing APLIS model with a soil water routine. The APLIS method is presented first, followed by the newly established soil water routine and finally the combination of both methods. The last point refers to the explanation of the evaluation method for the recharge estimations, and the application of climate scenario data for recharge simulations.

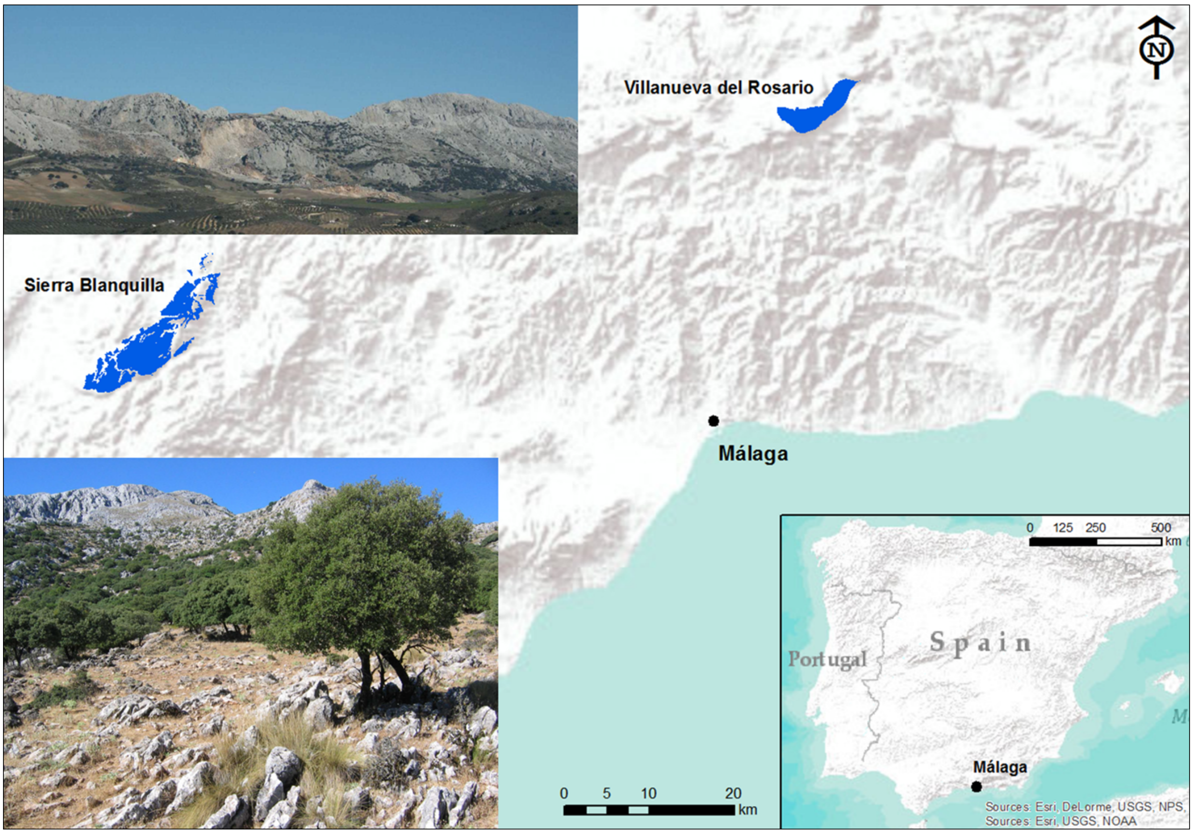

Figure 3.1: Location of the Villanueva del Rosario and Sierra Blanquilla system in southern Spain near Malaga. Impressions of the landscape in the study region (MARÍN, 2009).

3.1 Study areas

3.1.1 Villanueva del Rosario Study Area

The Villanueva del Rosario (Vva. del Rosario) karst system is located about 30 km north of Malaga in Andalusia in southern Spain and is part of the Sierra de Camarolos and Sierra del Jobo aquifer (Fig. 3.2). The relief is rugged and elevations range from 600 to 1.640 m above sea level (a.s.l.) (MARÍN *et al.*, 2015).

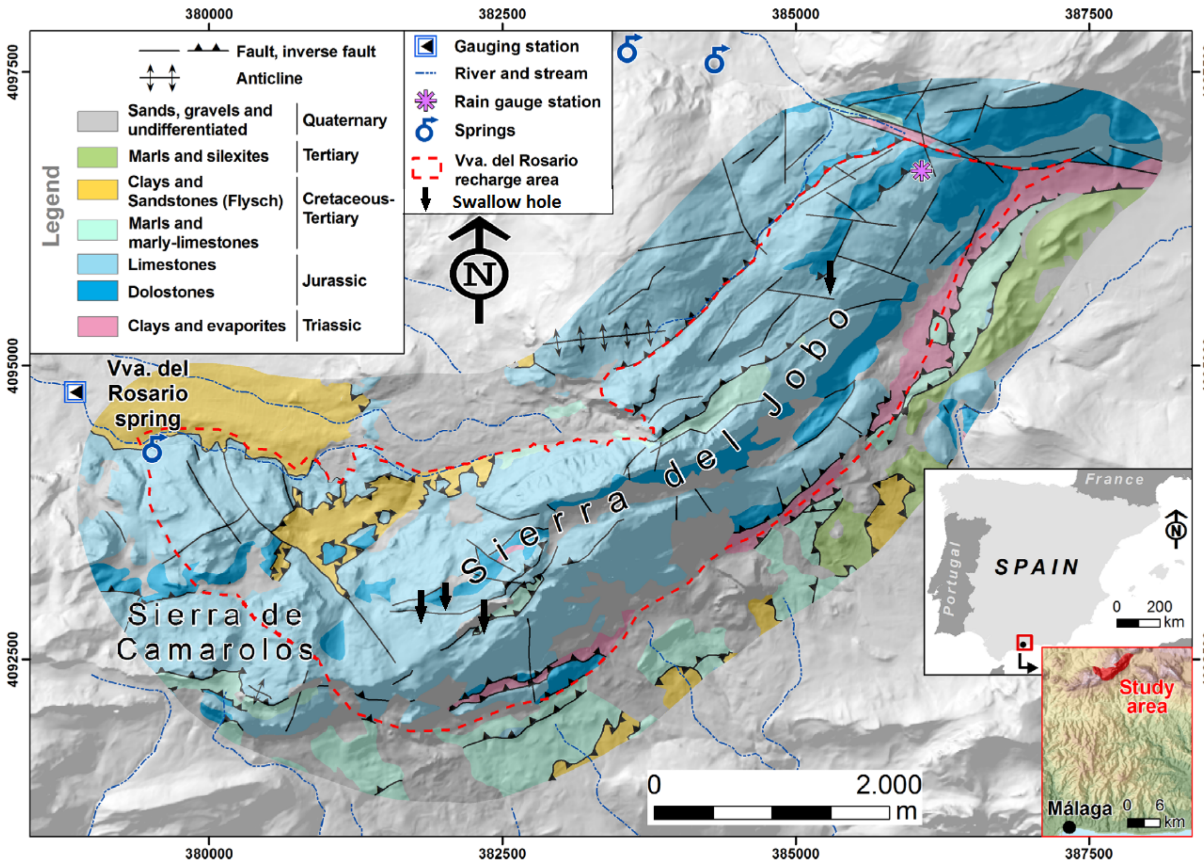

Figure 3.2: Location of the Vva. del Rosario catchment in southern Spain and geological map of the study area (HARTMANN *et al.*, 2014b, modified after MARÍN *et al.*,2015).

Climate

In this area a temperate Mediterranean climate prevails with rainfall occurring mainly in autumn and winter and less during springtime, due to wet winds coming from the Atlantic Ocean. The mean annual precipitation is 760 mm, whereas precipitation is below 600 mm in the lower parts and up to 900 mm in the higher parts of the study area. There are only temperature records for the lower areas of the area available where the mean annual temperature is close to 14 °C (MARÍN *et al.*, 2015).

Geology

The aquifer beneath Sierra de Camarolos and Sierra del Jobo is situated within the Betic Cordillera and consists of 400 to 450 m thick Jurassic carbonate rocks (Peyre, 1974 in Marín *et al.*, 2015). These carbonate rocks (dolostones and limestones) lay between Upper Triassic clays with evaporite rocks (mainly gypsum) underneath, and Cretaceous-Paleogene marly-limestones and marls on top. North and south of the study area are outcrops of Flysch-type clays and sandstones (Fig. 3.2). The geologic structure of the aquifer shows ENE-WSW lying folds, which induced the formation of overthrusts, with vergence towards S-SE. The structure in general is affected by more recent fractures in a mainly NW-SE direction (Martín-Algarra, 1987 in Marín *et al.*, 2015). Karst features with large karrenfields, dolines and uvalas developed mainly on Jurassic limestone. Furthermore, some swallow holes are present in the Rosario catchment (Fig. 3.2) which become active during storm events or heavy rainfall. There is no proof for the existence of caves in the study area despite investigations of speleological groups (Marín *et al.*, 2015).

Soil & Vegetation

Two different soil types can be found in the study area. Soil patches of leptosols with a thickness of less than 30 cm developed on the carbonate outcrops. Less permeable soils with a silty-clayey texture and a thickness of 10-70 cm cover the Cretaceous marls. The predominant vegetation consists of Mediterranean scrubland with patchy forest (Mediterranean forest and pines from reforestation). There are scattered farming activities over the carbonate outcrops which represent few potential sources for water contamination (Marín *et al.*, 2015).

Hydrology

The Vva. del Rosario system has a recharge area of around 14 km^2 and is part of the Sierra de Camarolos and Sierra del Jobo aquifer (28 %). The aquifer consists of fractured and karstified Jurassic carbonate rocks. It is limited at almost all its borders, except in the southwest and northeast (Mudarra *et al.*, 2014b), by low permeable materials (Triassic, Flysch clays, and Cretaceous-Paleogene marls) (Marín *et al.*, 2015, Fig. 3.2). The boundaries of the system were delineated by hydrogeological studies and multitracer tests (Mudarra *et al.*, 2014b). Recharge to the system takes place by concentrated or diffuse infiltration of rainfall, and discharge occurs toward the northern border of the carbonate outcrops and thus toward the Vva. del Rosario spring (770 m

a.s.l.). The groundwater flows mainly in NE-SW and S-N direction. The water of Vva. del Rosario spring (260 l/s historic annual mean discharge) is important for Vva. del Rosario village, as it serves as drinking water supply. The spring shows a quick response to precipitation events with several sharp and significant peaks per hydrological year in the discharge hydrograph (Marín *et al.*, 2015). The above mentioned investigations with the combined use of artificial and natural tracers in the Vva. del Rosario system show that the system is highly karstified. This leads to a quick drainage of water and low capacity of natural regulation (conduit flow system). Furthermore, the experiments demonstrated that the global response of the system (including diffuse infiltration) is quicker and more sensitive than the response produced from point infiltration (sinkholes) (Mudarra *et al.*, 2014b).
The Vva. del Rosario system is a well investigated system and several studies have been performed on the aquifer where further detailed information about the hydrogeological characteristics of the system is given (Mudarra *et al.*, 2011; Mudarra & Andreo, 2011; Mudarra *et al.*, 2014a,b).

3.1.2 Sierra Blanquilla Study Area

Climate, Geology & Soil

The second study area Sierra Blanquilla (Fig. 3.3) is part of the Serranía de Ronda. The site is located south-west of the city of Malaga with altitudes ranging from 580 m to 1.505 m a.s.l. and with a steep and rugged relief. The characteristics of the study site are similar to the Vva. del Rosario system. The climate is also of Mediterranean type, although with a higher mean annual rainfall of 850 mm (for the period 1964/65-2010/11) and a mean annual temperature of 13.5 °C (period 1981/82-1996/97) for the altitudes between 575 and 1290 m a.s.l.. The same stratigraphic groups as in the Vva. del Rosario system are found in the Sierra Blanquilla. The lowest formation is formed by Triassic clays and evaporites. The intermediate formation of Jurassic dolostone and limestone constitutes the main aquifer, and the formation on top consists of Cretaceous-Paleogene marls and marly limestones. The geological structure shows a NE-SW orientation and like in the Vva. del Rosario system karrenfields, dolines and uvalas developed as well as swallow holes. When soil is present, it is only a few centimeters or some decimeters thick, if it occurs in flat valleys and dolines. Vegetation is scarce, with patches of vegetation in the highlands. In the western sector of Sierra Blanquilla some livestock activities exist, but the area is basically uninhabited (Barberá & Andreo, 2015).

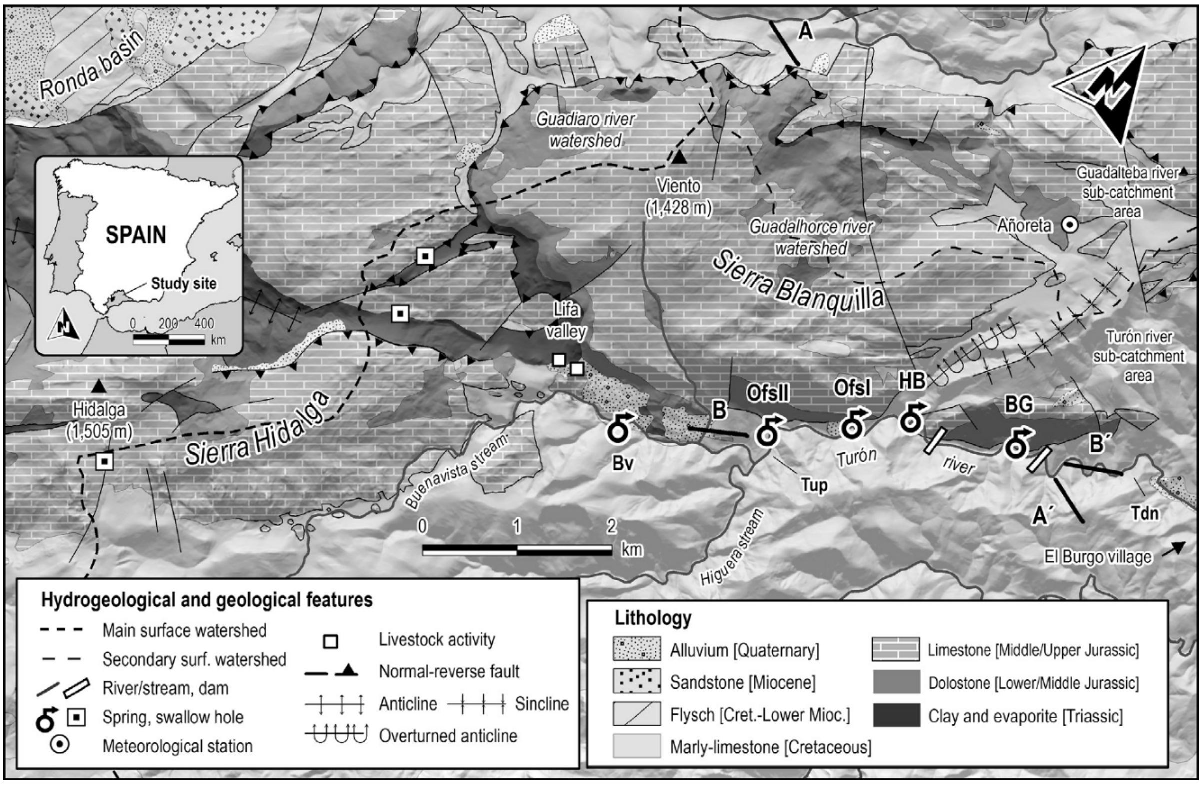

Figure 3.3: Location of the study area Sierra Blanquilla and the adjacent Sierra Hidalga, including hydrogeological and geological features as well as main surface watersheds. Abbreviations of spring and river monitoring sites: Bv: Buenavista spring (is part of Sierra Hidalga system), OfsI and OfsII: Overflow springs, HB: Hierbabuena spring, BG: El Burgo spring, Tup and Tdn: Turón river sections upstream and downstream of the main discharge area of Sierra Blanquilla aquifer (Barberá & Andreo, 2015).

Hydrology

In hydrological terms there is a difference to the Vva. del Rosario system, since there are interactions between surface water and groundwater in the second study area. Two river catchments are located in the area (Fig. 3.3), the Guadiario river watershed and the Guadalhorce river watershed, which is further divided into the Guadalteba river and the Turón river sub-catchment. The Turón river represents the most important hydrological feature in the study area. During high flow periods the river gets water from surface runoff generated in the southern part of the catchment (Buenavista and Higuera streams) and from groundwater discharge of the carbonate aquifers. During low flow conditions the water in the Turón river solely originates from groundwater of the carbonate aquifers (Sierra Blanquillla system and also adjacent Sierra Hidalga aquifer). The aquifers themselves are also fractured and/or karstified with a low capacity of natural regulation (conduit flow system). Recharge occurs mainly by infiltration of rainfall through carbonate outcrops producing sharp peaks in the discharge hydrograph, and to some extent by losing rivers and streams. The perennial springs El Burgo (BG, 600 m a.s.l., mean discharge 2007-2010: 2350 l/s) and Hierbabuena (HB, 645 m a.s.l., mean discharge 2007-2010: 110 l/s) located at the southern border of the area (Fig. 3.3), are the two most important points for groundwater discharge of the Sierra Blanquilla system. During high flow conditions after heavy rainfall, two overflow springs (OfsII, 655 m a.s.l., OfsII, 670 m a.s.l.) become active in addition to the groundwater discharge of the two perennial springs. Additionally, two artificial dams with 20 and 25 m height, located downstream shortly after these springs, affect their hydrodynamic regime. They initiate a buffering effect reducing timing and magnitude of peak discharge. Moreover, due to the dams a higher water table during high flow occurs and the water storage capacity increases at the Sierra Blanquilla aquifer. Water which is temporarily stored in the reservoirs is used for water supply of the village of El Burgo (Barberá & Andreo, 2015). The recharge area of the Sierra Blanquilla system is around 40 km^2. It was calculated using discharge data of the system (Chap. 3.4).

3.2 Data Availability

The section begins with a table (Tab. 3.1) summarizing all data that has been used in the course of this thesis and continues with a description of the different data sets.

3.2.1 Meteorological Data

The precipitation and evapotranspiration time series were prepared for the model in hydrological years lasting from October to September. To have one month for model warm-up the month September was also included in the model input.
Potential evapotranspiration data was obtained from temperature data applying the Thornthwaite equation (Thornthwaite, 1948).
The precipitation and temperature data of the meteorological station Cortijo de Jobo (Vva. del Rosario system, Fig. 3.4) were provided as complete time series from October 1990 until September 1999 and from September 2006 until October 2009.
For the Sierra Blanquilla system the meteorological data had to be supplemented. The precipitation times series provided by CEHIUMA ranged from 09/01/2007 until 07/31/2010, whereby data from 10/24/2007 until 05/12/2010 were from the Añoreta meteorological station(Fig. 3.4), from 09/01/2007 until 10/23/2007 from the weather station in Jimena de la Frontera, a village around 80 km to the south-west of Sierra

Table 3.1: List of inputs for the soil water balance routine and the correction method for the study sites Vva. del Rosario and Sierra Blanquilla, and data for evaluation of the new method. E_p: Potential evapotranspiration, P: Precipitation, RR: Recharge rate, Q: Spring discharge, CEHIUMA: Research group for hydrogeology of the University of Malaga (http://cehiuma.uma.es/).

Data type	Study site	Time period	Source
P [mm/d]	Vva. del Rosario	09/2006-09/2009 10/1990-09/1999	Meteo station Cortijo de Jobo, Data provided by CEHIUMA, and it is already published in Hartmann *et al.* (2014b)
	Sierra Blanquilla	09/2007-09/2010	Meteo station Añoreta, Data provided by CEHIUMA, and it is already published in Barberá & Andreo (2015)
E_p [mm/d]	Vva. del Rosario	09/2006-09/2009 10/1990-09/1999	Meteo station Cortijo de Jobo, Data provided by CEHIUMA, and it is already published in Hartmann *et al.* (2014b)
	Sierra Blanquilla	09/2007-09/2010	Meteo station Añoreta, Data provided by CEHIUMA, and it is already published in Barberá & Andreo (2015)
Climate scenario data P & E_p [mm/d]	Vva. del Rosario Sierra Blanquilla	09/1989-09/2099	Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP), (Hempel *et al.*, 2013)
Soil depth [cm]	Vva. del Rosario Sierra Blanquilla		FAO Harmonized World Soil Database (HWSD), (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012)
Esri ArcGIS Grid of APLIS RR [%]	Vva. del Rosario		Data provided by CEHIUMA, already published e.g. in Hartmann *et al.* (2014b)
	Sierra Blanquilla		Data provided by CEHIUMA, already published e.g. in Barberá & Andreo (2015)
Q [l/s] Evaluation data	Vva. del Rosario Sierra Blanquilla	2006/07-2008/09 2007/08-2008/09	Data provided by CEHIUMA, already published in Hartmann *et al.* (2014b); Barberá & Andreo (2015)

Blanquilla aquifer, and from 05/13/2010 until 07/31/2010 the times series was completed applying an interpolation method. To complete the time series until 09/30/2010 for the purposes of this thesis, it was assumed that there was no precipitation in August and September 2010.
The provided temperature time series ranged from 10/24/2007 until 05/12/2010, only with data from the Añoreta meteorological station. To get a complete time series from 09/01/2007 until 09/30/2010 the time series was gap-filled with the daily mean temperatures of the available temperature data.

These measured meteorological data were used to evaluate the new extended APLIS method. Additionally, the method was applied to climate scenario data (Chap. 3.5), which are presented in the following section.

3.2.2 Climate Scenario Data

Investigating the evolution of groundwater recharge in the future under changing climatic conditions, required meteorological data from climate models.
The climate model data were taken from the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP). The ISI-MIP is a modeling project combining impact models across different sectors and scales to investigate climate change impacts at different levels of global warming. The different sectors involved in the ISI-MIP fast track, which took place between January 2012 and January 2013, were water, agriculture, biomes, coastal infrastructure, and malaria as a health impact. For all these sectors different global impact models were applied. For the atmospheric CO_2 concentration the four representative concentration pathways (RCP) were used (Warszawski *et al.*, 2014). These four emission scenarios describe pathways towards reaching different radiative forcing trajectories and are displayed in Tab. 3.2 (Moss *et al.*, 2010). To get the associated climate data, five different general circulation models (GCM) (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, and NorESM1-M) were used providing climate grid datasets with 0.5°x 0.5°resolution. The five GCMs represent a selection of models which have been used in the Climate Model Intercomparison Project (CMIP5). They were selected to cover a broad range of projected global mean temperature and relative precipitation changes (Warszawski *et al.*, 2014). Detailed information about the bias-correction method for the climate data in the ISI-MIP are described in Hempel *et al.* (2013).

For the modeling purposes in this thesis the climate data from these five models, and only for the worst scenario (RCP8.5) were used. Grids were provided in netCDF format and temperature and precipitation time series were obtained. The grid values were transferred to Microsoft Excel files. The potential evapotranspiration was again calculated following the Thornthwaite approach (THORNTHWAITE, 1948).
Both study sites were located across the borders of two 0.5°x 0.5°grid cells of the climate data grids (Fig. 3.4) and thus two values per day, study site, and model were available. Hence, the precipitation and potential evapotranspiration data of the climate models were compared with the measured data from the meteorological stations of the study sites. The mean values appeared to be the most consistent with the measured data and it was thus decided to always take the mean values of the two climate scenario data sets of each meteorological parameter and climate model as input time series.
A description of the application of the climate scenario data within the recharge simulations can be found in Chap. 3.5.

Table 3.2: Representative Concentration Pathways (RCP) (MOSS *et al.*, 2010).

Name	Radiative forcing	Concentration [p.p.m.]	Pathway
RCP8.5	>8.5 W m^{-2} in 2100	>1,370 CO_2-equiv. in 2100	Rising
RCP6.0	~6 W m^{-2} at stabilization after 2100	~850 CO_2-equiv. (at stabilization after 2100)	Stabilization without overshoot
RCP4.5	~4.5 W m^{-2} at stabilization after 2100	~650 CO_2-equiv. (at stabilization after 2100)	Stabilization without overshoot
RCP2.6	Peak at ~3 W m^{-2} before 2100 and then declines	Peak at ~490 CO_2-equiv. before 2100 and then declines	Peak and decline

3.2.3 Soil Depth

Soil depth data was needed for the estimation of the maximum water storage capacity of the soil (V_{max}) which is a parameter in the soil water routine (Chap. 3.3.2). The data from the Harmonized World Soil Database (HWSD) consist of a 30 arc-second raster image file and a attribute database comprising the soil properties. The raster and the database were connected by a join in ArcGIS based on the attribute MU_GLOBAL representing the soil mapping units. This enables the visualization of all the data contained in the database in a GIS software. The database states the reference soil depth. To approximate the actual soil depth, relevant depth limiting soil phases, obstacles to roots and occurrence of impermeable layers have to be considered (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012). However, for the purpose of this thesis the reference soil depth was sufficient. As the entire soil volume is relevant, and not just the part that is available to plants.

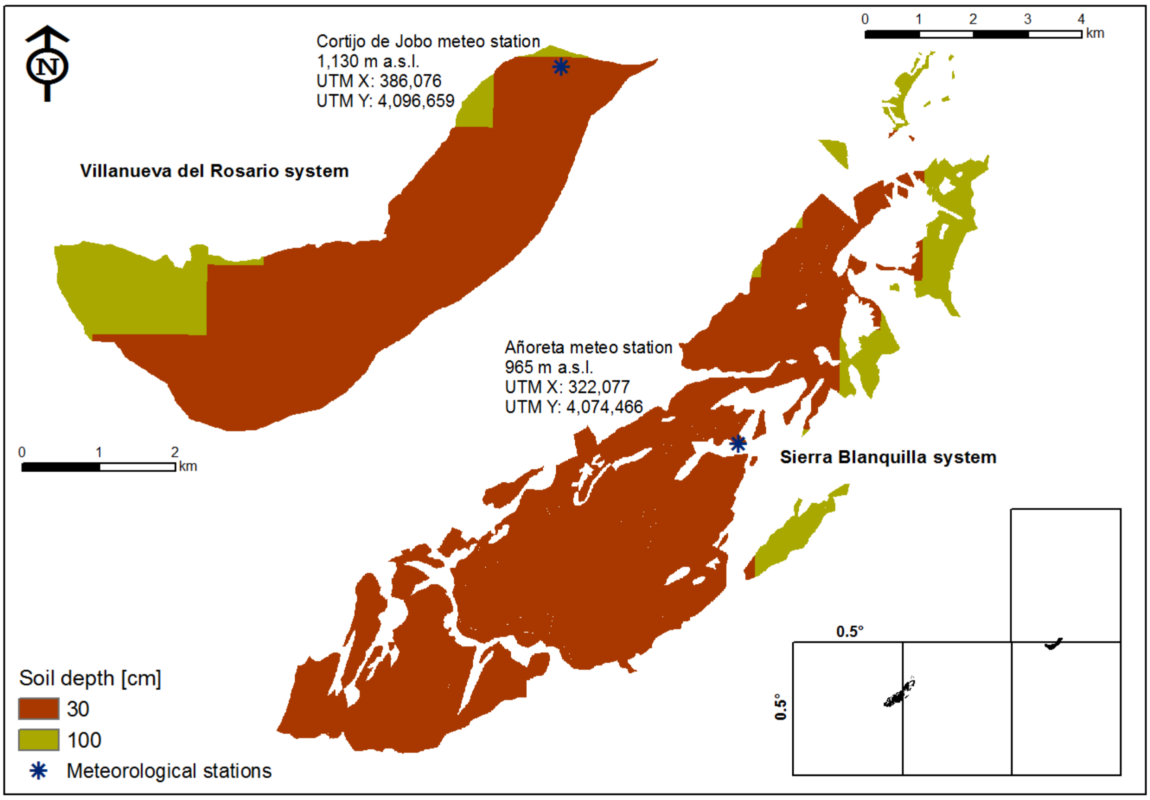

Figure 3.4: Soil depths of the study sites Vva. del Rosario and Sierra Blanquilla (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012). Location of meteorological stations providing data for this study, a.s.l.: above sea level. right: The four grid cells of the climate model data sets which provided data for the model runs with climate scenario data.

In both study sites, only 100 cm and 30 cm soil depth occurred (Fig. 3.4). Soils with a high clay content with porosities of $35 - 65\,\%$ (Blume *et al.*, 2010) develop on carbonate rock. Assuming a porosity of $50\,\%$, the maximum storage of the soil was 500 mm (100 cm) and 150 mm (30 cm) respectively. To speed up the calculations in the model runs the average values of the maximum storage volumes were used for the entire catchments. Thus, only a single value for the entire study area, rather than a

raster needed to be calculated during the recharge calculations (Chap. 3.3.2). The mean maximum storage volume was derived by calculating the mean depths from the HWSD raster for the study areas, before multiplying the mean depths with the porosity value of 50 %. The obtained mean V_{max} values were 210.47 mm for the Vva. del Rosario study area and 187.14 mm for the Sierra Blanquilla study area.
Furthermore, the HWSD raster was projected into the coordinate system of the APLIS recharge rate raster of the Vva. del Rosario system (ED_1950_UTM_Zone_30N), and was assigned the same cell size (5x5 m) as this raster. Since the APLIS raster of the Vva. del Rosario system was the first data set received, its coordinate system was used for all rasters in this thesis.

3.2.4 Recharge Rates Grids

The grids with the APLIS recharge rates for the two study sites (Fig. 3.5) were provided by the CEHIUMA. The method of APLIS for producing such recharge rate grids is described in Chap. 3.3.1.

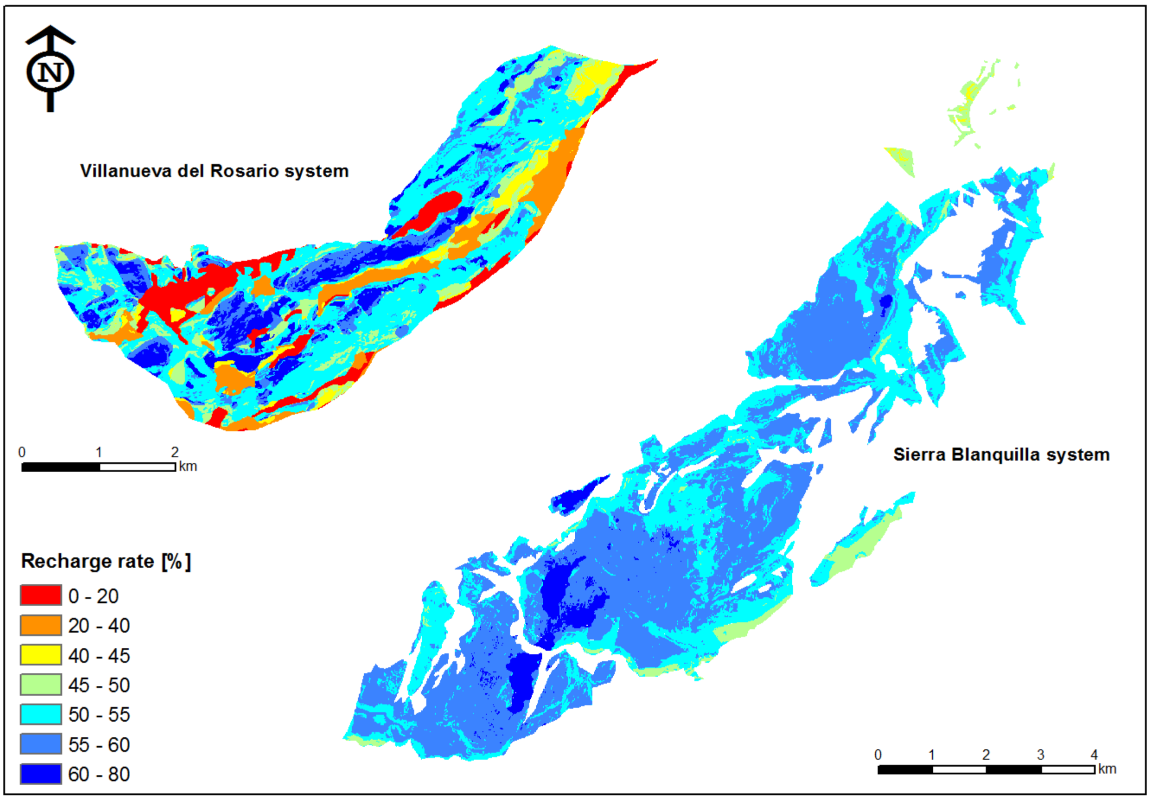

Figure 3.5: APLIS recharge rates provided by CEHIUMA for Vva. del Rosario and Sierra Blanquilla study areas.

Like the HWSD raster the APLIS recharge rate raster of the Sierra Blanquilla system was also projected to ED_1950_UTM_Zone_30N coordinate system. The cell size of 10 x10 m was retained.

3.2.5 Spring Discharge data

Spring discharge data were needed for the evaluation of the method.
For the Vva. del Rosario system the spring discharge data published in Hartmann *et al.* (2014b) have been used. They provided annual discharge sums in mm for the hydrological years 2006/2007 (dry), 2008/2009 (wet) and for the annual mean from 2006/2007 until 2008/2009.
For the Sierra Blanquilla system the provided discharge time series supplied data for the hydrological years 2007/2008 and 2008/2009 in l/s. The data set represents a net discharge time series (T_{dn} - T_{up}) of the gauging station Turón down and Turón up (Fig. 3.3). T_{up} measures discharge which consists of surface runoff of Buenavista and Higuera stream and of spring discharge from Buenvista spring. At T_{dn} the measured discharge is the sum of the amount from T_{up} and the groundwater discharge from Sierra Blanquilla. Hence, the difference of the two gauging stations at the Turón river can be used as groundwater discharge from the Sierra Blanquilla aquifer (Barberá & Andreo, 2015).
The further procedure of evaluation is described in Chap. 3.4.

3.3 Methods for Groundwater Recharge Simulation

The chapter has been divided into three sections. First the APLIS method for calculation of spatially distributed recharge is described, followed by the description of the developed soil water routine for temporally distributed recharge simulation. The third part describes the combination of both of these methods.

3.3.1 APLIS - Spatial Distribution of Recharge

APLIS is a GIS based model which estimates the mean annual recharge ($\bar{\mathrm{R}}$) in carbonate aquifers, expressed as a percentage of annual precipitation, based on the variables altitude (A), slope (P), lithology (L), infiltration landforms (I), and soil type (S) (ANDREO *et al.*, 2008) and depending on the correction coefficient of recharge ($\mathrm{F_h}$) which describes the hydrogeological characteristics of the exposed bedrock (MARÍN, 2009) :

$$\bar{R} = \frac{A + P + 3L + 2I + S}{0.9} \cdot F_h \qquad (3.1)$$

The method was established using eight aquifers in southern Spain, which represented a wide range of climatic and geological characteristics. The characteristics of the aquifers were examined with a particular focus on physical characteristics, namely climatic, topographic, lithologic, geomorphologic and pedologic characteristics. Analysis of these parameters revealed the most important parameters with the greatest influence on groundwater recharge which were then used to develop the APLIS equation. For each of the above mentioned parameters a map in a GIS has to be created applying the categories from 1 to 10 for each variable (Tab. 3.3). Only the infiltration landform parameter and the correction coefficient of recharge are limited to three categories, and two respectively. A value of 1 represents minimal and a value of 10 expresses maximum influence on aquifer recharge. The division by 0.9 ensures that there is always some degree of recharge but it never reaches 100 % of the precipitation. Hence, recharge rates range between 8.88 % and 88.8 %. The weight of the variables in the equation represents its importance on the formation of recharge. This means lithology and infiltration landforms have three times, and two times respectively, as much influence on recharge formation as the variables altitude, slope, and soil. The abbreviations of the parameters are the Spanish initials for the variables and form the name of the method APLIS. APLIS estimates autogenic recharge which includes direct recharge, localised recharge via swallow holes, and indirect recharge from the bed of superficial water courses (ANDREO *et al.*, 2008).

Table 3.3: Ratings for the APLIS input variables altitude, slope, lithology, infiltration landforms, soil, and correction coefficient of recharge. The data range expressions, e.g. (600-900] mean, the value 600 is not included and 900 is included in this class (ANDREO *et al.*, 2008; MARÍN, 2009).

Variable	**Score**	**Variable**	**Score**
Altitude [m] A		Slope [%] P	
≤ 300	1	≤ 3	10
(300-600]	2	(3-5]	9
(600-900]	3	(5-10]	8
(900-1,200]	4	(10-15]	7
(1,200-1,500]	5	(15-20]	6
(1,500-1,800]	6	(20-30]	5
(1,800-2,100]	7	(30-45]	4
(2,100-2,400]	8	(45-65]	3
(2,400-2,700]	9	(65-100]	2
>2,700	10	>100	1
Soil S		Lithology L	
Leptosols	10	Limestones and dolostones karstified	10/9
Arenosols and xerososl	9	Limstones and dolostones fractured, slightly karstified	8/7
Calcareous regosols and fluvisols	8	Limestones and dolostones fissured	6/5
Euthric regosols and solonchaks	7	Gravels and sands	4
Cambisols	6	Conglomerates	3
Euthric cambisols	5	Plutonic and metamorphic rock	2
Histosols and luvisols	4	Shales, silts, clays	1
Chromic luvisols	3		
Planosols	2		
Vertisols	1		
Infiltration landforms I		Characteristics of exposed bedrock F_h	
Highly developed infiltration landforms	10	Aquifer-like characteristics	1
Medium developed infiltration landforms	5	Others	0.1
Scarce or no infiltration landforms	1		

The altitude was divided into groups of 300 m intervals in a one-by-one arithmetic progression, so that the higher the altitude the greater the precipitation, and hence the greater the recharge. For altitudes greater than 2.700 m, differences in recharge were imperceptible. Slope values were grouped into different sized groups with the highest category for the smallest slope values. The lower the slope the greater the recharge. For slope values greater than 100 %, recharge was assumed to be minimal and invariable. Scores were assigned to different types of lithology depending on their hydrogeological characteristics. APLIS is mainly intended to estimate recharge into carbonate aquifers. Thus, the scores 5 to 10 describe carbonate rock with a different degree of karstification. The more fractures and fissures are present, the more recharge is produced. Soil types were grouped depending on the characteristics of predominant thickness and texture according to the System of Environmental Information on Andalusia (Sinamb-A). Therefore, soils have maximum recharge values when they are not highly evolved with thin soil cover and coarse texture (score of 10). Whereas thick and clayey soils result in minimal recharge values (score of 1) (Andreo *et al.*, 2008).
Only three scores were assigned to the infiltration landform parameter describing the existence of infiltration structures and the potential capacity for infiltration. For the correction coefficient of recharge just two scores were differentiated. This factor distinguishes between exposed bedrock with aquifer characteristics (score of 10), i.e. appropriate lithology, porosity or level of karstification, and without such characteristics (score of 0.1). Hence, non-carbonate rock units in the research area are considered and too high recharge results for these parts are prevented (Marín, 2009).

The APLIS equation can easily be applied e.g. in ArcGIS with the *Raster Calculator* tool resulting in a raster with the recharge rates (Fig. 3.5). The mean recharge rate is the mean of all raster cells in the output recharge rate grid. Further on, multiplying the obtained APLIS recharge raster with the annual precipitation sum in the *Raster Calculator* tool results in a raster with the annual recharge sum. For the purpose of this thesis however, the APLIS recharge rate rasters were provided (Chap. 3.2.4) and had not to be calculated.

3.3.2 Soil Water Balance Routine - Temporal Distribution of Recharge

To simulate temporally distributed recharge a soil water routine was developed in Python (Python 2.7.2). All calculations in the routine are performed on a daily basis in three steps:

1) $E_a = E_p \cdot \frac{V_{t-1}}{V_{max}}$

2) $V_t = V_{t-1} + P - E_a$

3) If $V_t > V_{max}$:
$R_{dS} = V_t - V_{max}$
$V_{t+1} = V_{max}$
$Else$:
$R_{dS} = 0$
$V_{t+1} = V_t$

E_a: Actual evapotranspiration [mm]
E_p : Potential evapotranspiration [mm]
V_{t-1}: Water volume in the soil storage at time step t-1 [mm]
V_{max}: Maximum water storage capacity of the soil [mm]
V_t: Water volume in the soil storage at time step t [mm]
P: Precipitation [mm]
R_{dS}: Recharge [mm]
V_{t+1}: Water volume in the soil storage at time step t+1 [mm]

The land surface in karst areas with fractures and sink holes constitute good infiltration conditions, ans surface runoff may thus often be negligible. This allows for the estimation of recharge by the difference between precipitation and actual evapotranspiration (Hartmann *et al.*, 2014a). Therefore, precipitation represents the source of water for the model, consumption occurs through evaporation and transpiration. The potential evapotranspiration (E_p) is the amount of water, that would evaporate if sufficient water was available. Thus the E_p also describes the maximum possible evapotranspiration that can occur. Actual evapotranspiration (E_a) is the actual amount of evapotranspiration that is lost to the atmosphere (Pardo-Igúzquiza *et al.*, 2012).
E_a is calculated similarly to the approach in other models (e.g. TOPMODEL Beven & Kirkby, 1979; Butscher & Huggenberger, 2008; Fiorillo *et al.*, 2015; Le Moine *et al.*, 2007).

Recharge occurs when the water volume in the soil exceeds the threshold which is the maximum water storage capacity. The recharge amount results from the difference between the water volume and the maximum water storage volume. Moreover, a limit is integrated in the Python code, so that the filling of the soil storage can not become smaller than zero. The water volume in the soil storage is assumed to be zero at the beginning. That is why one month for model warm-up is included in the input time series. This establishes more realistic conditions for soil moisture at the start of the considered simulation period.
Input files which have to be provided for the soil routine are daily precipitation and potential evapotranspiration data as text files, containing just the values without date. Output files are text files containing daily values for recharge, actual evapotranspiration, and stored soil water volume. Moreover, text files with the mean annual recharge sum ($\mathrm{R_{aS}}$) and precipitation sum over the input time series are saved, together with a raster with the mean annual APLIS recharge sum ($\mathrm{R_{aA}}$). Therefore the soil routine calculates time series on a daily basis, but no spatially distributed values. Constant soil depth, precipitation, and evapotranspiration are assumed over the entire study site.

The data were prepared in Microsoft Excel including the rainfall and evapotranspiration values without date. Afterwards they were converted into a text file. The text file must not have any empty rows at the end of the file. This sometimes occurred after converting it from the Excel file and led to an error in the soil routine method.

3.3.3 Combination of Spatial and Temporal Recharge Distributions

To enable spatio-temporally distributed recharge estimations the APLIS method and the soil water routine were combined using a correction factor. The correction factor comprises the ratio of the mean annual recharge sum of the APLIS method ($\mathrm{R_{aA}}$) and the mean annual recharge sum of the soil water routine ($\mathrm{R_{aS}}$):

$$R_C = R_{dS} \cdot \frac{R_{aA}}{R_{aS}} \tag{3.2}$$

R_C: Corrected daily recharge [mm]
R_{dS} : Daily recharge of the soil water routine [mm]
R_{aA}: Mean annual recharge sum of APLIS [mm]
R_{aS}: Mean annual recharge sum of the soil water routine [mm]

Every daily recharge value from the soil routine ($\mathrm{R_{dS}}$) is multiplied with the correction factor. The mean annual recharge sum of the soil routine ($\mathrm{R_{aS}}$) is calculated through

multiplication of the mean daily recharge of the entire input time series by 365.25. The mean annual APLIS recharge sum (R_{aA}) is calculated by multiplying the APLIS recharge rate (Fig. 3.5) by the mean annual precipitation sum, which in turn results from multiplying the daily mean precipitation of the input time series by 365.25. Only for the Sierra Blanquilla system the correction factor for the measured data was not calculated using the entire time series of three years, but using only data of the year 2007/2008 (Chap. 3.4).
Due to the multiplication of the mean annual precipitation sum with the APLIS rate raster, R_{aA} also becomes a raster and consequently the correction factor is a raster as well. Thereby, the results of formula 3.2 are rasters as well, containing daily corrected spatially distributed recharge values. The method disaggregates the APLIS recharge rate into daily resolution which means that over the entire simulation period the mean annual corrected recharge of the new method is equal to the mean annual APLIS recharge. It must be noted that the introduced approach also allows for calculation of recharge rates greater than 100 %. This is due to the method of using a correction factor.

All these calculations are done along with the soil routine calculations in the same Python script. To get an overview of the model, a flow chart of the combined method is provided in Fig. 3.6.

For the analysis of the model results only the annual means were evaluated. It is not convenient to present daily recharge rasters and for the purpose of evaluation it was appropriate to calculate the annual sums. This means instead of applying formula 3.2 to every daily recharge value from the soil routine, it was applied to annual recharge sums. Moreover, for all examined time series the wettest and driest year and the annual mean over the time series were determined with regard to precipitation. And the corrected recharge sums were calculated only for these three cases.

For this purpose the resulting text file with daily recharge values from the soil routine was imported in Microsoft Excel to calculate annual sums (October-September). Afterwards, the three annual sums (wet, dry, average) were multiplied with the correction factor, which was put out from the Python model, using the *Raster Calculator* tool in ArcGIS. The results were rasters containing corrected annual recharge sums. Recharge rates were also calculated with the *Raster Calculator* tool by dividing the annual recharge sum by the annual precipitation sum and multiplying it with 100.

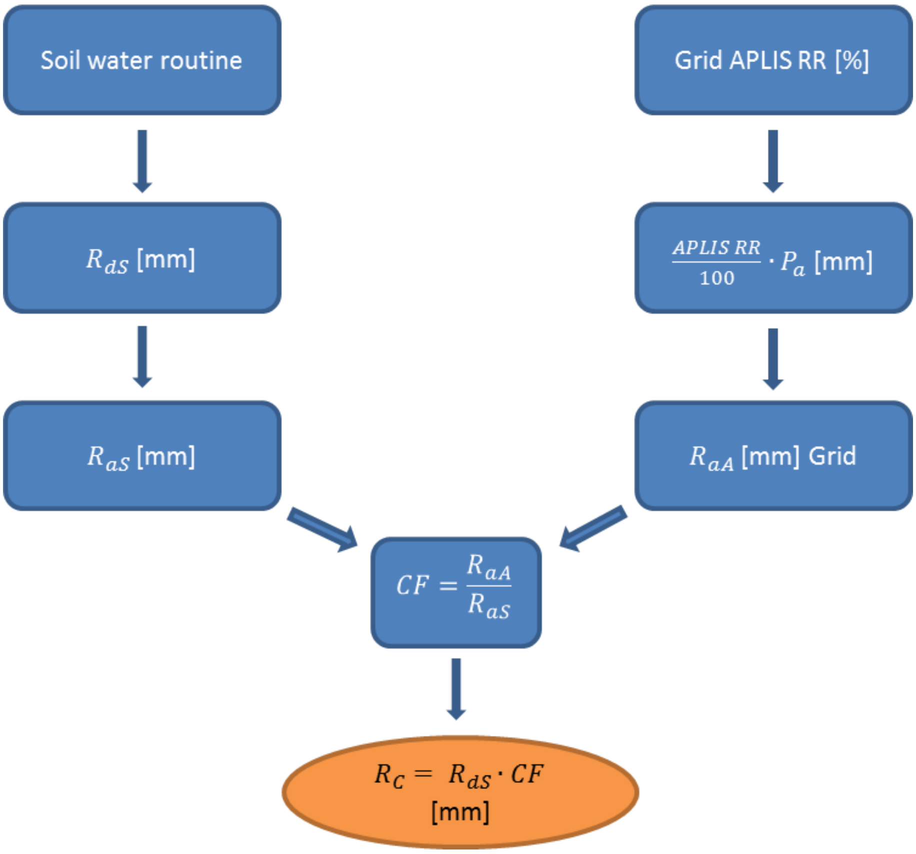

Figure 3.6: Flow chart of the combination of APLIS and the soil water routine. The soil water routine calculates daily recharge (R_{dS}) and the mean annual recharge sum of the time series (R_{aS}) is calculated. The mean annual APLIS recharge sum (R_{aA}) is determined through multiplication of the provided APLIS recharge rate (RR) with the mean annual precipitation of the time series (P_a). The corrected recharge (R_C) is calculated with formula 3.2 whereby the correction factor can also be applied to monthly or annual values.

Prior to the presented method another approach was tested using the available data for Vva. del Rosario system. It was based on the calculation of correction factors on an annual basis. The deviations of the annual E_a sums from the mean of all three annual sums (2006 – 2009) were calculated to use these as a correction factor for the APLIS recharge rates. The factors had to be subtracted from the APLIS rates to get the corrected rates. Resulting negative recharge rates were set to zero. However, having daily corrected recharge values instead of corrected annual recharge rates offers more options to work with afterwards, e.g. it is always easier to aggregate than to disaggregate data.

3.4 Evaluation of the Method

The new method was evaluated with observed spring discharge of Vva. del Rosario and Sierra Blanquilla system. The rate of discharge is equal to the mean annual recharge for a sufficiently long period of years and in aquifers which are not influenced by extractions through pumping (ANDREO *et al.*, 2008) and can thus be used for evaluation of the recharge simulations.
The available data for the Vva. del Rosario system already provided annual discharge sums in mm for the hydrological years 2006/2007 (dry), 2008/2009 (wet) and for the annual mean from 2006/2007 until 2008/2009. However, the discharge data for the Sierra Blanquilla system was provided in l/s.
To transform the data from l/s in mm/d the recharge area (A) was needed, which was determined using the annual discharge (Q) and precipitation (P) sum from 2007/2008 and the mean APLIS recharge rate (RR) for Sierra Blanquilla of the provided recharge rate raster (Q/P/RR=A). Subsequently, using the recharge area the data was transformed in mm/d and the annual sums for the two years were calculated. Although discharge data of two years were available just the data from 2007/2008 were used to calculate the recharge area due to the extremely high discharge in the year 2008/2009. This year was also identified as a wet year in the Vva. del Rosario area as shown in HARTMANN *et al.* (2014b) and would bias the calculations which are based on average values. The year 2007/2008 on the other hand was closer to an average year as indicated in HARTMANN *et al.* (2014b). This was also the reason for calculating the correction factor for the measured data of the Blanquilla system solely with data from 2007/2008 (Chap. 3.3.3). Useful evaluation data was only available for this year.
To evaluate recharge with observed discharge the recharge and discharge rates were compared. Consequently, the annual observed discharge was divided by the annual observed precipitation to calculate annual discharge rates.

3.5 Application of Climate Scenario Data

As described in Chap. 3.2.2 climate scenario data of five different global climate models were available to investigate the possible impact of climate change on groundwater recharge. The data was available for the time span from 1989 to 2099 and was divided into three time periods: present (1989 - 2009), future (2039 - 2059), and remote future (2079 - 2099).

The acquired temperature and precipitation data were used for the soil water routine to calculate daily recharge values as explained in Chap. 3.3.2. The correction factor was then applied in different ways, and two cases were tested. The first option was to calculate a separate correction factor for each model and present time period, which was subsequently used for the future and remote future time period of the respective model. The second option was to use the same correction factor, which had been calculated with the data of the measured meteorological time series also for the recharge simulations with the modeled climate data. However, for various reasons the second approach proved not to be successful and was therefore rejected. Further explanations can be found in the discussion (Chap. 5.2.3). The results are displayed in the Annex (A.1). Consequently, first approach was selected.

4 Results

The chapter has been divided into three sections. It begins with a description of the results of the application to the model on historic data and goes on presenting the results of the evaluation of the new method with historic spring discharge data. The last section describes the results of recharge simulations applying the climate scenario data. All presented results were produced with the newly established method of extending APLIS with a soil water routine and thus combining spatially and temporally distributed recharge estimations. Therefore the term 'new method' refers to the combined APLIS and soil routine method.

4.1 Application to Historic Data

Firstly, the results of all years with available measured data are presented in a table. The second part illustrates the spatial distribution of recharge rates.
The table with the results of the recharge simulations with the new method (Tab. 4.1) summarizes annual sums of precipitation, recharge, and recharge rates for the available hydrological years with measured data for both study sites. The results in the table are the spatial mean values of the corrected recharge rasters which were calculated as described in Chap. 3.3.3. For Vva. del Rosario the correction factor was calculated using the entire time series from 2006 till 2009. For Sierra Blanquilla the factor was calculated using just the data from the year 2007/2008 as explained in Chap. 3.4.

Generally, it can be observed that the Sierra Blanquilla area received more rainfall on average than Vva. del Rosario. This is consistent with the data give in in the description of the study sites (Chap. 3.1). Sierra Blanquilla also showed higher recharge rates on average compared to Vva. del Rosario study site. Extremely high recharge rates for Sierra Blanquilla occurred in the years 2008/2009 and 2009/2010. The regarded time series for Vva. del Rosario presented a broad range of different precipitation sums from extremely wet to extremely dry years with no simulated recharge. In general moderate to high recharge rates were simulated with a maximum rate of 67 %. The mean recharge rates over the time series were lower for Vva. del Rosario respectively higher for Sierra Blanquilla compared to the original APLIS recharge rates (Tab. 4.2).

Table 4.1: Results of the recharge simulations for the study sites Vva. del Rosario and Sierra Blanquilla for the application of the new method to available measured meteorological data. P: Precipitation, R: Recharge, RR: Recharge rate. Conspicuous high values are highlighted.

	Year	**P [mm]**	**R [mm]**	**RR [%]**
Rosario	1990/1991	524.1	188.9	36
	1991/1992	692.3	303.1	43.8
	1992/1993	481.4	114.8	23.8
	1993/1994	628.2	242.5	38.6
	1994/1995	353.1	0	0
	1995/1996	1556.1	1045.9	67.2
	1996/1997	1419	933.5	65.8
	1997/1998	1050.1	638	60.8
	1998/1999	275.1	0	0
	2006/2007	642.4	209.6	32.6
	2007/2008	682.7	239.3	35.1
	2008/2009	932.2	603.4	64.7
	mean	769.7	376.6	39
Blanquilla	2007/2008	834	465.7	55.8
	2008/2009	883.9	864.7	97.8
	2009/2010	1263	1269.5	100.5
	mean	993.6	866.6	84.7

Taking a closer look on the results for Vva. del Rosario it can be observed that for the year 1993/1994 more recharge was generated than for the year 2006/2007, although that year received a higher precipitation amount. Comparing the years 1991/1992 and 2007/2008 it can be seen that almost the same precipitation amount occurred, but disproportional more recharge was generated in 1991/1992. The same effect can be observed for the Sierra Blanquilla aquifer. The years 2007/2008 and 2008/2009 received similar amounts of rainfall, but very different recharge sums were generated.

To get an impression of the temporal distribution of rainfall and recharge, the time series of the just mentioned hydrological years for Sierra Blanquilla and Vva. del Rosario area are displayed in Fig. 4.1 and 4.2. Generally, the plots of the time series show the generation of recharge as response to precipitation events. For Sierra Blanquilla the high-intensity rainfall events in autumn 2008 generated recharge, whilst the rainfall events in autumn 2007 could not exceed the storage capacity. And also later during the hydrological year 2008/2009 intense rain events lasting several days produced great amounts of recharge. For Vva. del Rosario the years 1991/1992 and 1993/1994 during which more recharge was generated, indicate that more rainfall events with a higher intensity occurred during these years. Furthermore, the temporal distribution of rainfall was more evenly distributed in the year 2007/2008 than 1991/1992 and the precipitation events in autumn 2007 were not large enough to exceed the threshold of the maximum storage capacity of the soil. Generally, an influence of the temporal precipitation pattern on recharge simulations could be observed for both study sites.

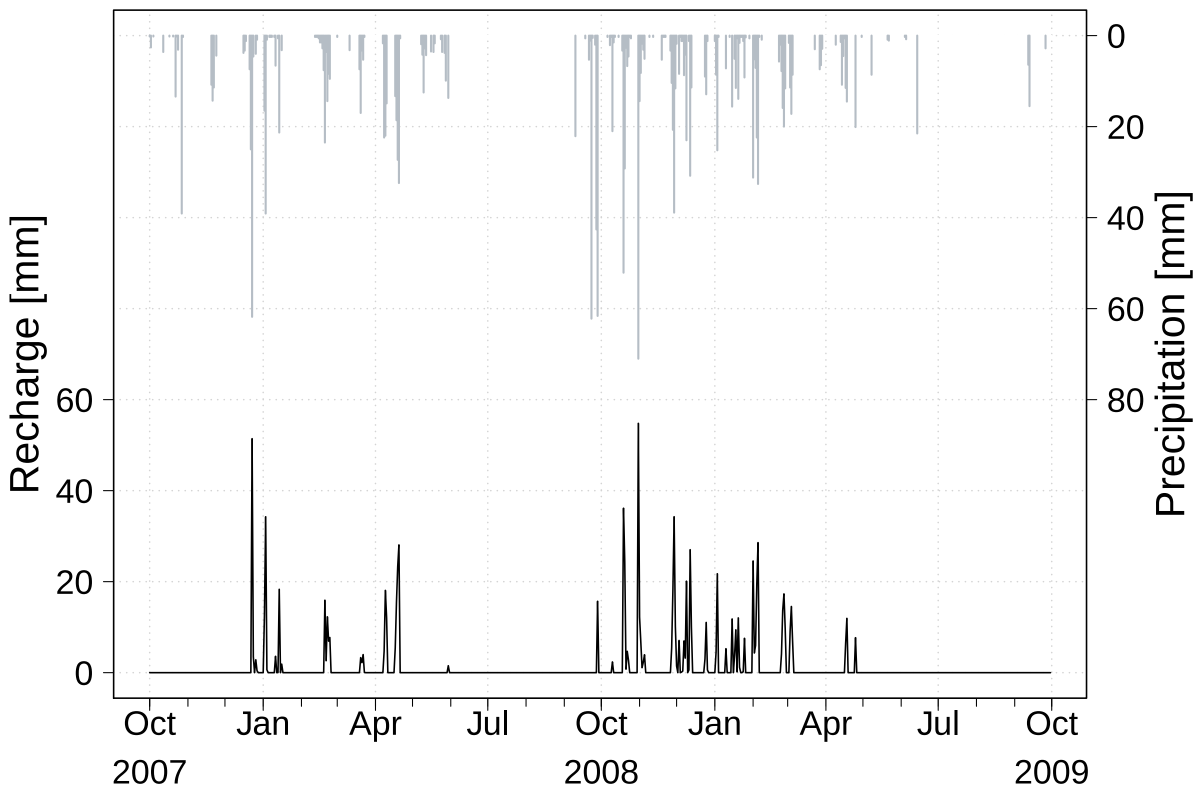

Figure 4.1: Simulated recharge and measured precipitation for the years 2007/2008 and 2008/2008 for Sierra Blanquilla study site.

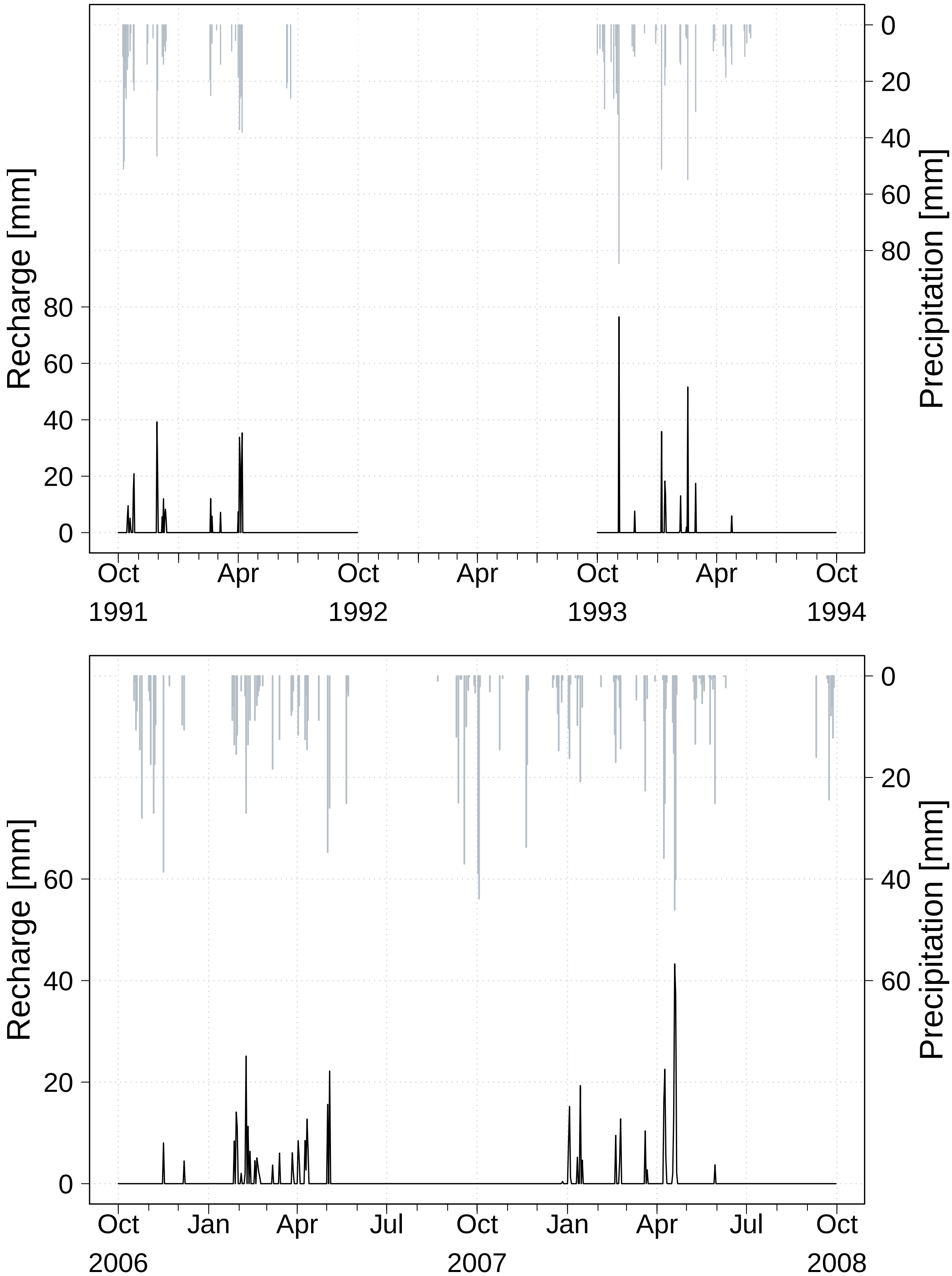

Figure 4.2: Top: Simulated recharge and measured precipitation for the years 1991/1992 and 1993/1994. Bottom: Simulated recharge and measured precipitation for the years 2006/2007 and 2007/2008. Both graphs display data of Vva. del Rosario.

Fig. 4.3 summarizes the results of both study sites in different plots showing the relation between precipitation and recharge. The same plots for displaying the data were chosen as in Martos-Rosillo *et al.* (2015) in order to compare the results later on.

Only the data of Vva. del Rosario were fitted to regression lines since only three years of measured data were available for Sierra Blanquilla. The upper graph in Fig. 4.3 displays the annual recharge versus annual precipitation with a linear approximation and a significant coefficient of determination ($R^2 = 0.99$). The higher the precipitation, the higher the recharge. In the middle graph the recharge rate was plotted against the annual rainfall and a logarithmic approximation was fitted to the data points. Additionally, a significant determination coefficient of $R^2 = 0.92$ could be observed. The lower the annual precipitation the greater is the slope in the logarithmic approximation. The bottom graph displays the recharge rate versus annual recharge with a polynomial approximation. Also for this case, a significant determination coefficient of $R^2 = 0.99$ was achieved. For low recharge rates the slope of the polynomial equation is steep. For high annual recharge sums the recharge rate seems to stabilize between 60 and 70 %.

Considering the three displayed years of Sierra Blanquilla, different results could be observed. The years 2008/2009 and 2009/2010 showed considerably higher recharge values than simulated recharge in Vva. del Rosario. However the recharge of the year 2007/2008 lay in the range of the values of Vva. del Rosario area.

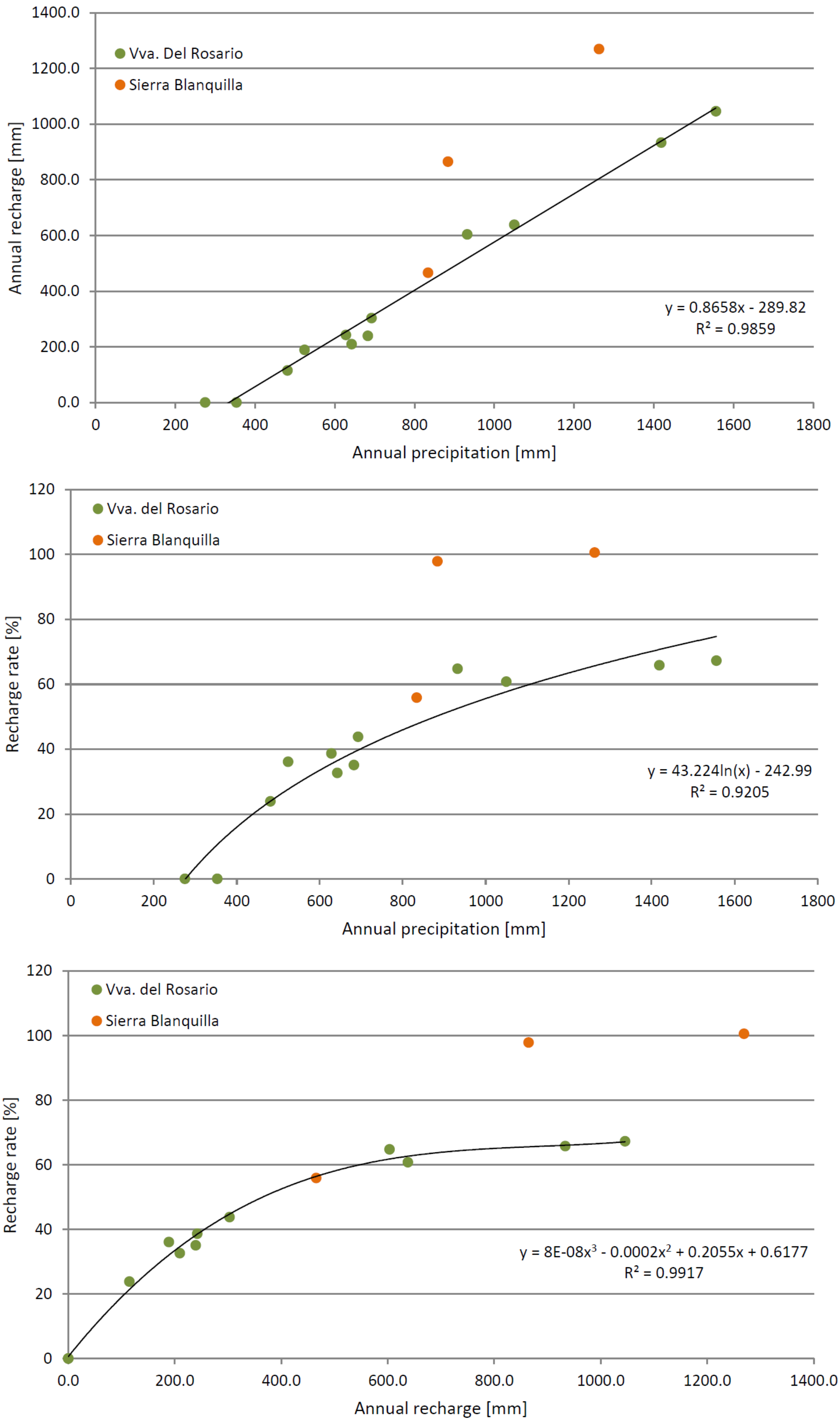

Figure 4.3: Top: Annual simulated recharge versus annual precipitation. Middle: Simulated recharge rate versus annual precipitation. Bottom: Simulated recharge rate versus annual recharge. Each point corresponds to one year. 12 years in total for Vva. del Rosario and three years for Sierra Blanquilla.

4.1.1 Spatial distribution of recharge

The spatial distribution of simulated recharge rates for both study sites are illustrated in Fig. 4.4 and 4.5. To show a selection, only the years with available spring discharge data for evaluation (Chap. 4.2) are displayed.

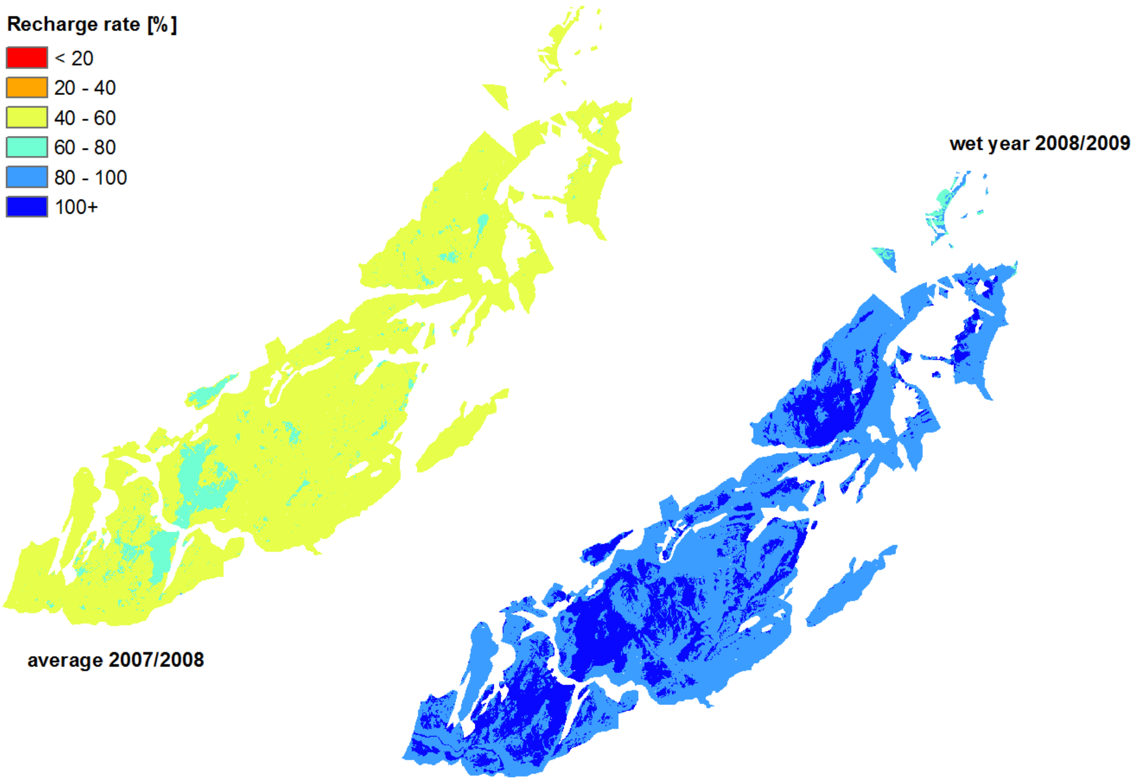

Figure 4.4: Spatial distribution of simulated recharge rates for Sierra Blanquilla for the average year 2007/2008 and the wet year 2008/2009.

In the Sierra Blanquilla study area the recharge rates ranged between 76 and 140 % for the average year 2007/2008, and between 43 and 80 % for the wet year 2008/2009. The upper part of the catchment is not displayed on the geological map (Fig. 3.3) but for the remaining study area high recharge rates could be associated with Jurassic geology and the area of Viento peak. No low recharge rates occurred in the catchment. Comparing the results with the geological map also showed, that those parts of the Sierra Blanquilla area comprising of Cretaceous and Triassic geology were not reproduced in the resulting recharge raster as they were also not included in the provided APLIS recharge rate raster (Fig. 3.5).

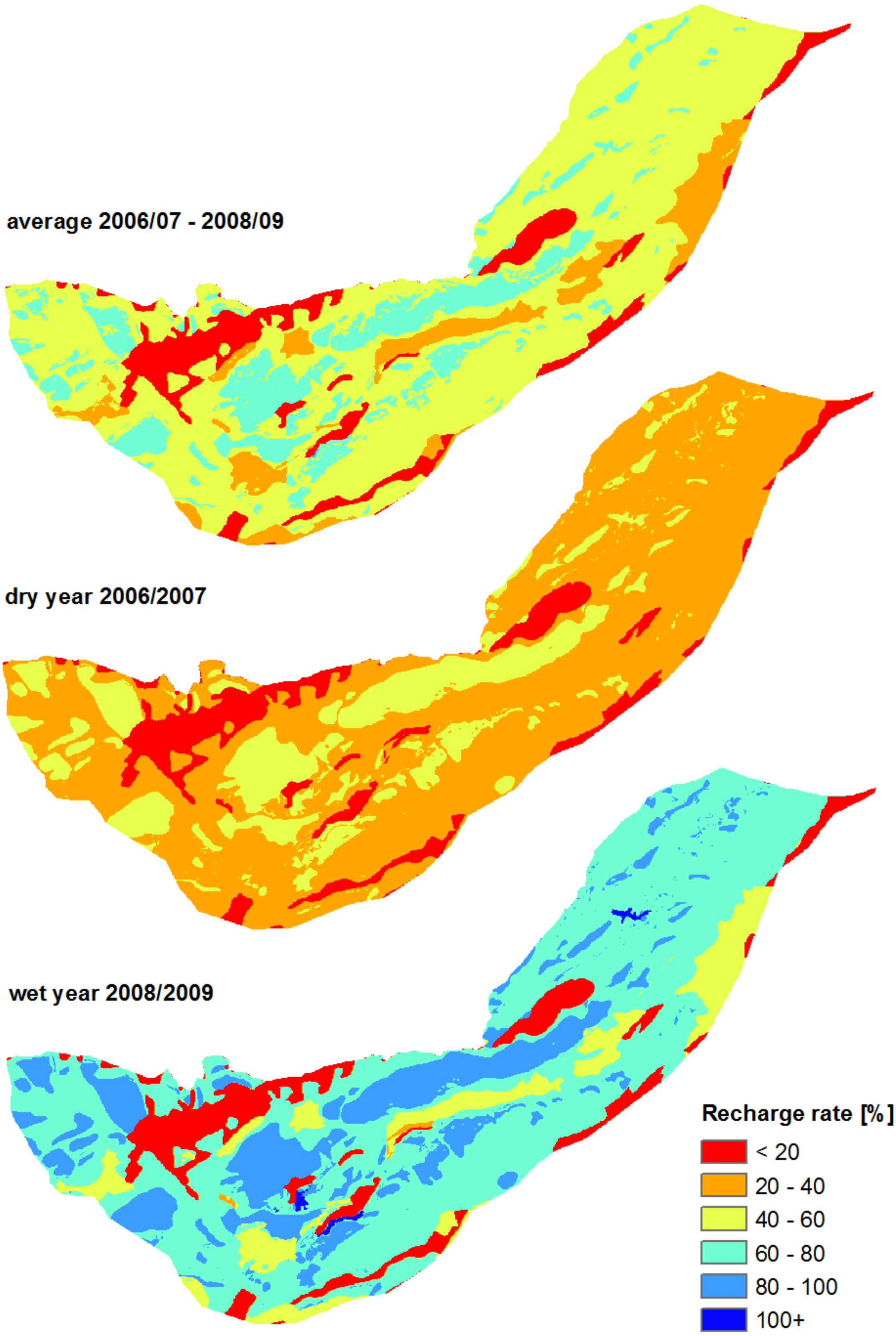

Figure 4.5: Spatial distribution of simulated recharge rates for Vva. del Rosario for the average year over the period 2006-2009, the dry year 2006/2007, and the wet year 2008/2009.

Looking at the APLIS input maps (Fig. A.3, A.4) it can be seen that they only consist of a few classes, except the slope parameter. The pattern of the infiltration landform parameter was reflected in the recharge rate rasters. In the pattern for the wet year also an influence of the slope parameter could be distinguished.
In the Vva. del Rosario study area the recharge rates for the annual average between 2006 and 2009 ranged from 1.2 to 80 %. In the dry year the minimal rate was 0.9 % and the maximum rate 56 %, and for the wet year 1.7 % respectively 111 %. The lowest rates occurred in Cretaceous-Tertiary and Triassic geology and moderate rates in the Quaternary geology of the study area. The highest recharge rates were produced in Jurassic limestones and dolostones. In the wet year the swallow holes (Fig. 3.2) could be identified showing the highest recharge rates. The spatial pattern of recharge reflected the pattern of the APLIS input parameter, as can be seen from the APLIS input maps in the Annex (Fig. A.1, A.2). Especially the pattern of lithology, infiltration landform parameter and correction coefficient of recharge could be identified in the recharge rasters.

For both study sites unrealistic high recharge rates over 100 % occurred. However, in the Vva. del Rosario study site this occurred only in small parts of the area whereas about half of the Sierra Blanquilla area was affected in the wet year. In general the range of recharge values was smaller for Sierra Blanquilla compared to Vva. del Rosario.

4.2 Evaluation with Historic Data

The results of the evaluation for both study sites are summarized in Tab. 4.2. The annual precipitation sums for the evaluation years are displayed, as well as the recharge rates calculated with the new method, and the discharge rates of observed spring discharge of the karst systems. Aside from this, also the recharge rates of the original APLIS method are displayed.

As explained in Chap. 3.4 the discharge data for the hydrological years 2006/2007, 2008/2009 and the average from 2006/2007 till 2008/2009 were available for the Vva. del Rosario system. The year 2008/2009 represented a wet year and 2006/2007 a dry year, as can be seen comparing the annual precipitation sums. The table shows similar results for the recharge rates of the new method and the rates of observed spring discharge. Comparing the rates clearly shows the difference between the rates of the new method, observed data, and the APLIS rates. For the wet year the APLIS rate was lower, and for the dry year higher than the rates of the new method and of the discharge data.

For the Sierra Blanquilla system the discharge data for two hydrological years were available, whereas the year 2008/2009 represented the wet year and the year 2007/2008 represented the average year. The extremely high discharge rate in the year 2008/2009 stood out, as well as the high recharge rate for that year (marked orange).

Table 4.2: Results of the evaluation of the new method for Vva. del Rosario and Sierra Blanquilla study sites. P: Precipitation, R: Recharge, RR: Recharge rate, Q_{spring}: Spring discharge, DR: Discharge rate. Conspicuous high values are highlighted.

			New method		Observed		APLIS
	Year	**P** [mm]	**R** [mm]	**RR** [%]	$\mathbf{Q_{spring}}$ [mm]	**DR** [%]	**RR** [%]
Rosario	2008/2009 wet	932.2	603.4	64.7	692.3	74.3	46.6
	2006/2007 dry	642.2	209.6	32.6	173.5	27	46.6
	2006/07-2008/09 average	752.4	350.8	46.6	391	52	46.6
Blanquilla	2008/2009 wet	883.9	864.7	97.8	1144.3	129.5	55.8
	2007/2008 average	834	465.7	55.8	465.3	55.8	55.8

For both study areas the recharge rates of the new method for the average year equaled the APLIS recharge rate. This is due to the structure of the new method, where the mean annual recharge sum of the corrected recharge equals the mean annual recharge sum of APLIS, as explained in Chap. 3.3.3. The discharge rate of Sierra Blanquilla was also equal to the APLIS recharge rate, because the recharge area had been calculated with the recharge rate (Chap. 3.4).

4.3 Application to Climate Scenario Data

This section describes the results of the recharge simulations with the climate scenario data. Again, the second part deals with the spatial distribution of recharge rates in the study sites and the evolution of the distribution in the course of projected climate change.

As explained in Chap. 3.5, two possibilities were tested for the application of the correction factor to the climate model data. The results presented here were calculated using a separate correction factor for each climate model and present time period, which were subsequently used for the future and remote future time periods.

Table 4.3 summarizes the annual sums of precipitation, recharge, and recharge rate for the wettest, driest, and average years of each considered time period (present, future, and remote future). The values in the table are the spatial mean values of the corrected recharge rasters which were calculated as described in Chap. 3.3.3.

The purpose of the application of climate scenario data was not to discuss and compare the differences between the climate models, but to cover a certain range of different climate change projections. Thus, the single values of recharge estimations with the separate climate model data were not relevant for this study and only the ensemble means of the results for all five climate models are presented here. However, to get an idea of the value range of the results for the different models, also the maximum and minimum values of each five models results are displayed together with the ensemble mean (Tab. 4.3). Moreover, conspicuous results of individual models are mentioned in the text. The individual results for all climate models can be found in the Annex (A.2, A.3).

Regarding the overall results of the climate models, it can be observed that precipitation and recharge, and thus also recharge rates were decreasing along with the three time periods representing present, future and remote future.

As for the measured data, it can be observed that the Sierra Blanquilla area received more rainfall on average than Vva. del Rosario and also showed higher recharge rates. Moreover, the average annual precipitation sums of the present time period of the climate models were lower than the measured average annual rainfall sums for both study sites.

It occurred three times that the calculated recharge rates for the wet years for some models exceeded 100 %. For these three cases the recharge rate was set to 100 %.

Table 4.3: Results of the recharge simulations for the study sites Vva. del Rosario and Sierra Blanquilla applying the new method to climate scenario data. Displayed are the ensemble means (bold) of all five climate models for each time period (present, future, remote future), and always for the wettest, driest, and average year over the time period. Above the ensemble mean values are the maximum values and beneath the minimum values (grey) of the results of all models. P: Precipitation, R: Recharge, RR: Recharge rate.

		Vva. del Rosario			Sierra Blanquilla		
		P [mm]	R [mm]	RR [%]	P [mm]	R [mm]	RR [%]
Present (1989-2009)		946.4	1112.1	117.5	1038.8	1079.6	106.5
	wet	**834.8**	**743.5**	**83.4**	**913.1**	**874.3**	**92.1**
		659.2	384.5	58.3	711.2	653.1	83.4
		392.5	128.8	32.8	426.6	21.6	5.1
	dry	**312.5**	**25.8**	**6.6**	**324.5**	**4.3**	**1**
		222.2	0	0	229.2	0	0
		589.9	275	46.6	641.4	358.2	55.8
	average	**552.4**	**257.5**	**46.6**	**596.5**	**333.1**	**55.8**
		515.2	240.2	46.6	556.0	310.5	55.8
Future (2039-2059)		961.9	860.5	90.5	1070.4	1038.4	97
	wet	**764.6**	**607.0**	**78.8**	**838.4**	**697.2**	**82**
		580.9	406.6	69	657.4	471.7	71.7
		329.1	0	0	319.8	0	0
	dry	**260.6**	**0**	**0**	**255.4**	**0**	**0**
		216.6	0	0	200.3	0	0
		519.3	164.9	35	542.5	231	46
	average	**455.1**	**122.2**	**26.7**	**482.4**	**180.3**	**37.2**
		417.9	36.8	8.6	446.3	92.5	20.4
Remote Future (2079-2099)		792.3	560.3	80.1	811.6	572.8	76.5
	wet	**650.1**	**351.3**	**52.2**	**670.3**	**392.2**	**56.8**
		536.9	0	0	535.4	82.8	15.5
		227.6	0	0	224.4	0	0
	dry	**143.3**	**0**	**0**	**150.4**	**0**	**0**
		55.8	0	0	57	0	0
		375.1	62.8	20	405	111.2	27.5
	average	**332.9**	**49**	**14.9**	**350**	**76.1**	**21.7**
		285.5	15.5	4.7	297.4	40.5	11.7

As with the measured data, the recharge rates of the average years for the present time periods equaled the APLIS recharge rates for the corresponding study sites. Again, this is due to the structure of the method where the annual average corrected recharge over the time series is equal to the annual average APLIS recharge. Generally, high recharge rates were generated with the climate model data for the wet years but no recharge for the dry years. Only the climate data of one model resulted in the generation of recharge in the present time period. The displayed minimum and maximum values show that the climate data generated a certain range of different recharge results. Differences in the results are not visible for the dry years, but for the wet and average years of the time periods. For Vva. del Rosario the data of one model even resulted in the simulation of no recharge for the wet year in the remote future. Moreover, for Vva. del Rosario the results for the wet years of one model suggested an increase in recharge from present to future and a decrease from future to remote future. However, recharge in the remote future was still higher than during the present time period. Thus, an overall increase in recharge was simulated by one model. Also for Sierra Blanquilla one model simulated an increase in recharge from present to future for the wet year, but a decrease for the remote future. The results of the models with an increase in recharge are highlighted in Tab. A.2 and A.3.

In order to highlight the evolution of the three variables precipitation, recharge, and recharge rate, the relative future change of theses variables compared to the present time period is plotted in Fig. 4.6.
The plots for the relative future change in rainfall and recharge for the ensemble means of the average years show similar results for both study sites. They clearly show the decrease for all variables in the future, whilst the decrease was enhanced in the remote future. The amount of recharge was decreasing for both study sites by around 80 % in the remote future.

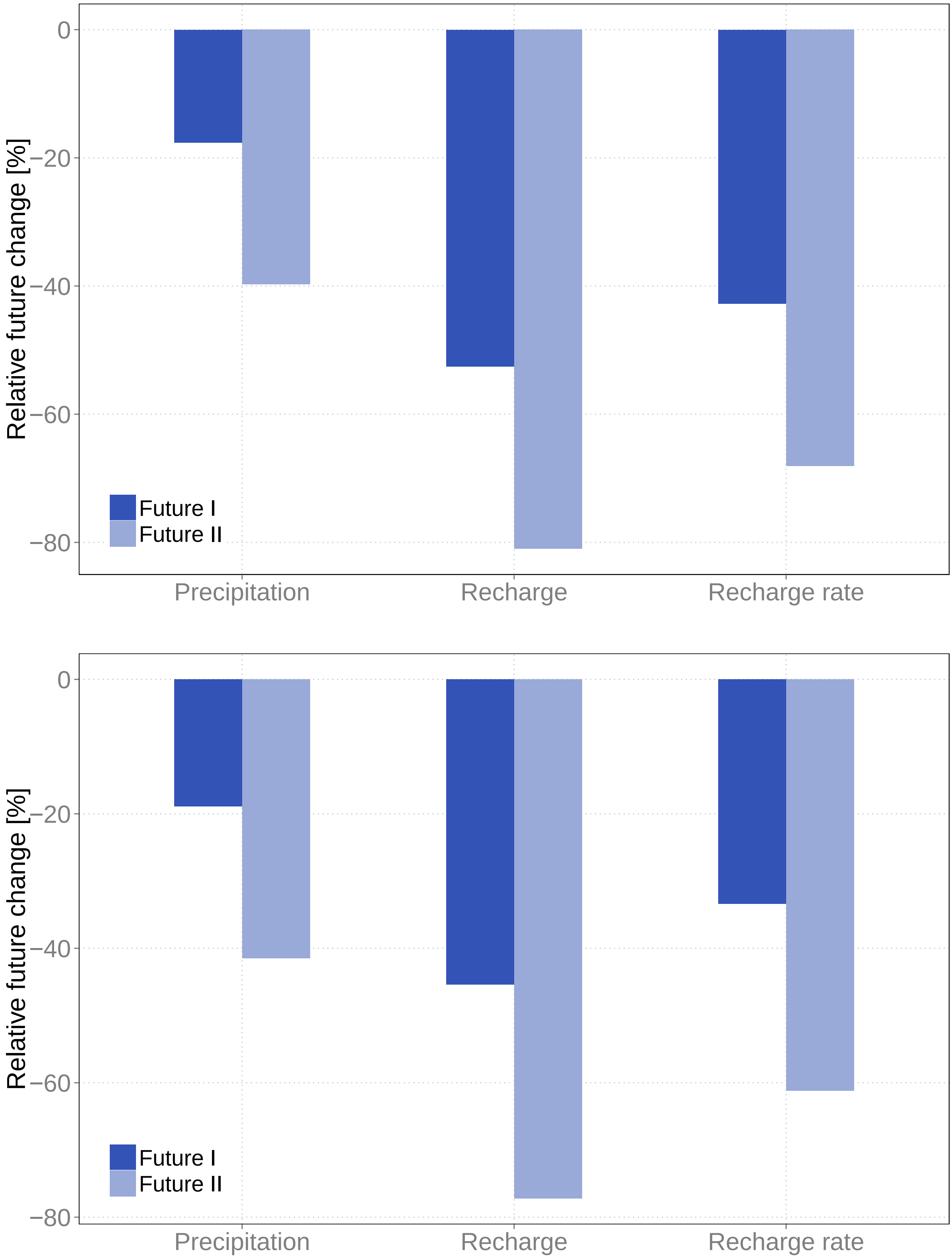

Figure 4.6: Relative future change of precipitation, recharge, and recharge rate for Vva. del Rosario (top) and Sierra Blanquilla (bottom) for the future (2039-2059) = Future I and remote future (2079-2099) = Future II time period. Displayed are relative changes of the ensemble mean values for the average years.

To get an impression of the range of values of the calculated correction factors, these are listed in table 4.4 for the climate models as well as for the measured data.

Table 4.4: Correction factors calculated with historic data and climate scenario data for both study sites.

		measured	GFDL	HAD	IPSL	MIROC	NOR
Rosario	max	1.64	5.62	3.36	2.83	4.78	3.28
	min	0.03	0.09	0.05	0.04	0.07	0.05
	mean	0.96	3.28	1.96	1.65	2.79	1.91
Blanquilla	max	1.91	3.56	2.44	2.22	3.06	2.4
	min	1.03	1.93	1.32	1.21	1.66	1.3
	mean	1.33	2.49	1.7	1.55	2.13	1.67

The values displayed correspond to the maximum, minimum and mean values of the correction factor rasters. The differences between measured and climate model correction factors can clearly be distinguished, as the correction factors of the climate model data were considerably higher.

4.3.1 Spatial distribution of recharge

Also for the results with the climate scenario data, maps were created to analyze the spatial distribution of recharge and its development along the three time periods. For each study site and time period (present, future, remote future) the ensemble mean of the recharge rates of all five climate models for the average years is displayed (Fig. 4.7, 4.8).

The decrease in recharge under modeled future climate conditions could be observed in both study sites. In the Vva. del Rosario study area the recharge ranged between 1.2 and 80 % for the present time period and between 0.7 and 46 % respectively 0.4 and 26 % for the future and remote future time period. Again it could be observed that Cretaceous-Tertiary and Triassic geology produced least recharge and high recharge rates occurred in Jurassic geology, whereas the highest recharge rates occurred in Jurassic limestone. Moderate rates were present in Quaternary geology.

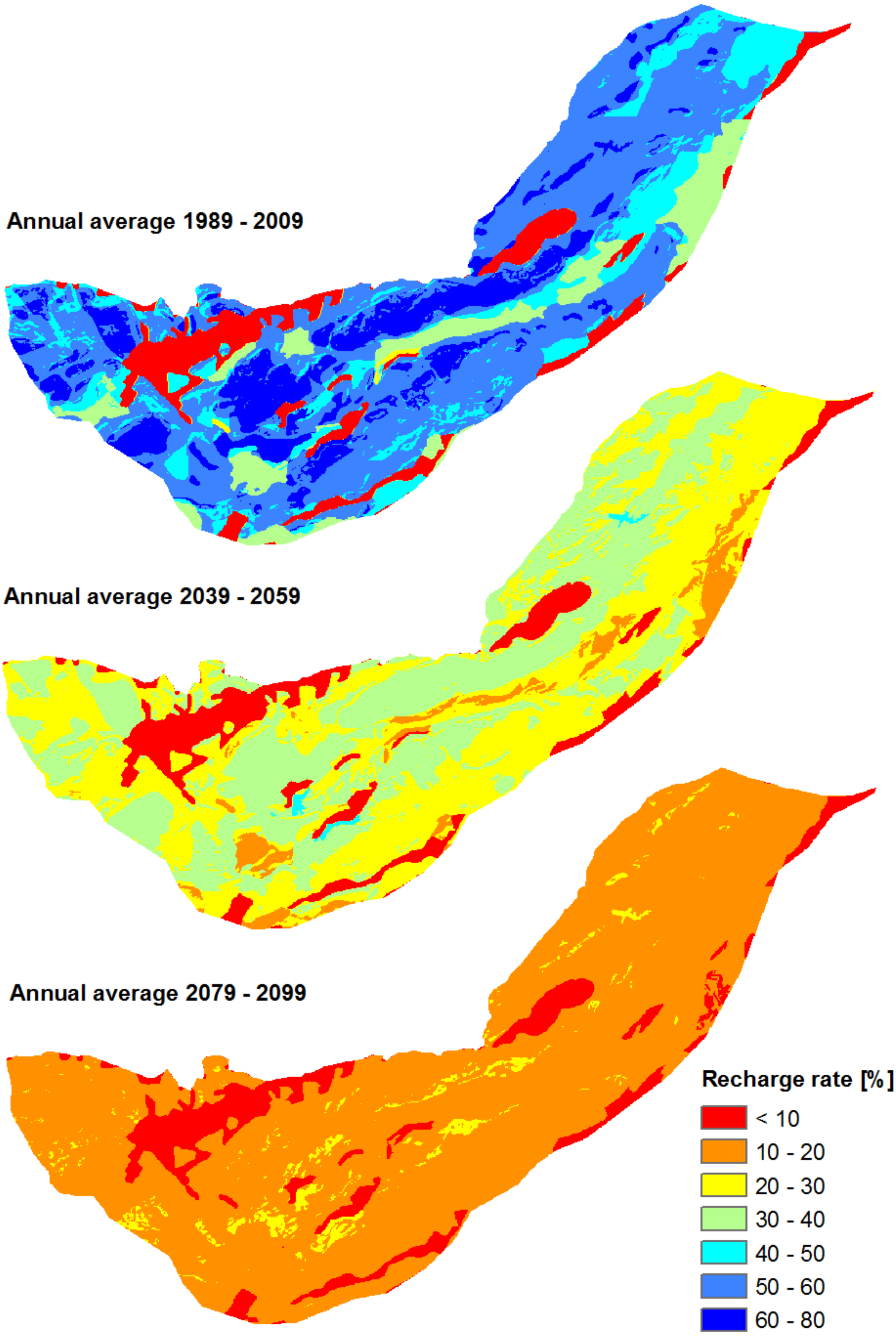

Figure 4.7: Spatial distribution of simulated recharge rates for Vva. del Rosario for the three time periods present (1989-2009), future (2039-2059), and remote future (2079-2099). Displayed are the ensemble means of the results for all five climate models for the average year.

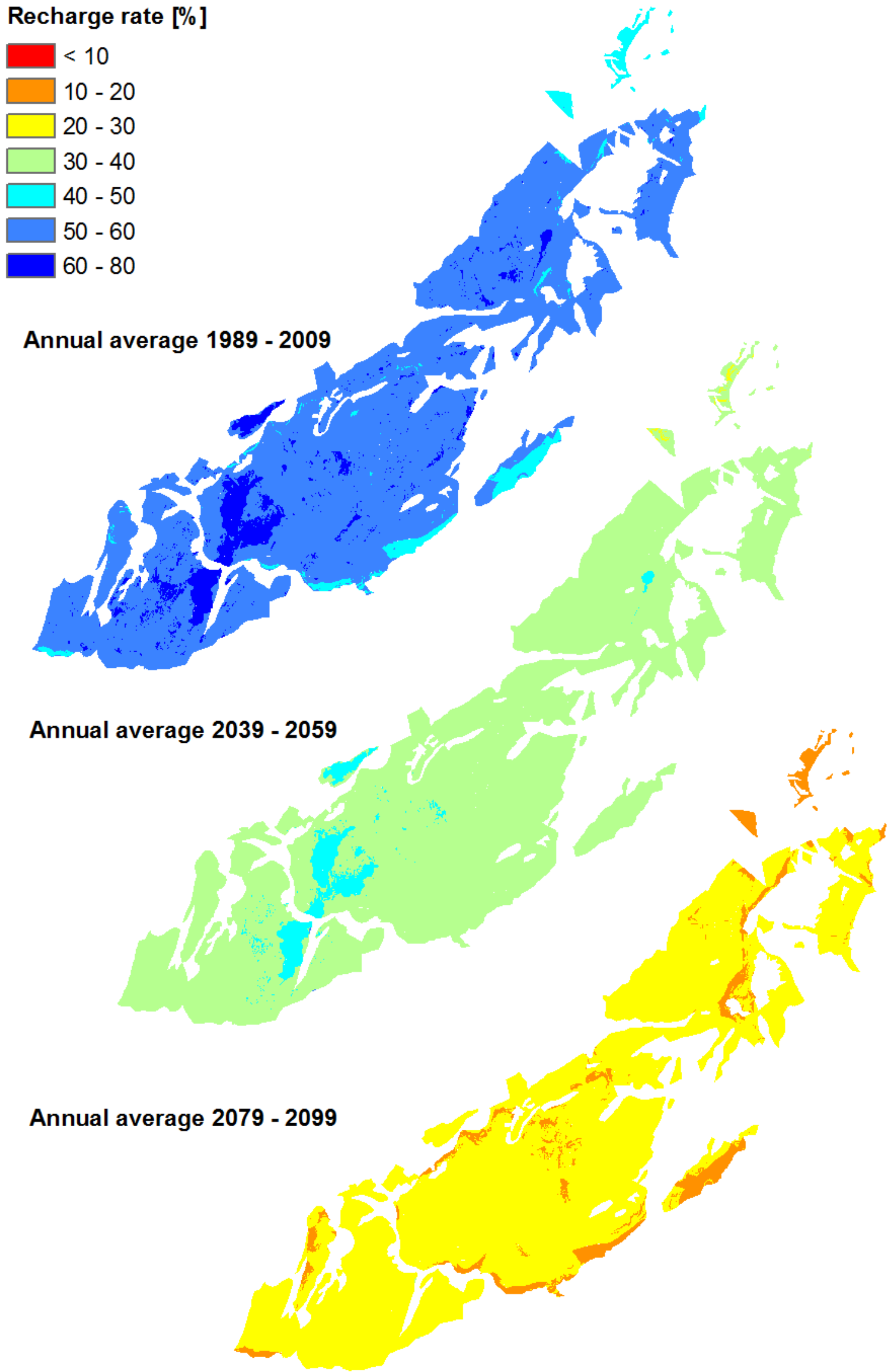

Figure 4.8: Spatial distribution of simulated recharge rates for Sierra Blanquilla for the three time periods present (1989-2009), future (2039-2059), and remote future (2079-2099). Displayed are the ensemble means of the results for all five climate models for the average year.

The pattern of the APLIS parameters lithology and infiltration landform was reflected in the spatial distribution of recharge, as well as the parameter for the correction coefficient of recharge.
For the Sierra Blanquilla study area the recharge ranged between 43 and 80 % for the present time period, and between 28 and 53 %, 16 and 31 % respectively, for the future and remote future time period. Also the same spatial pattern of recharge distribution as for the measured data occurred, with the highest rates in the area of Viento peak in Jurassic limestone. The lower rates in the present and remote future results were associated with Jurassic dolostone. For the present and remote future, an influence of the litholgy input parameter of APLIS could be recognized. Furthermore, for the present and future the pattern of the infiltration landform parameter was reflected in the recharge raster. The rates in the Sierra Blanquilla aquifer presented a smaller value range compared to Vva. del Rosario.

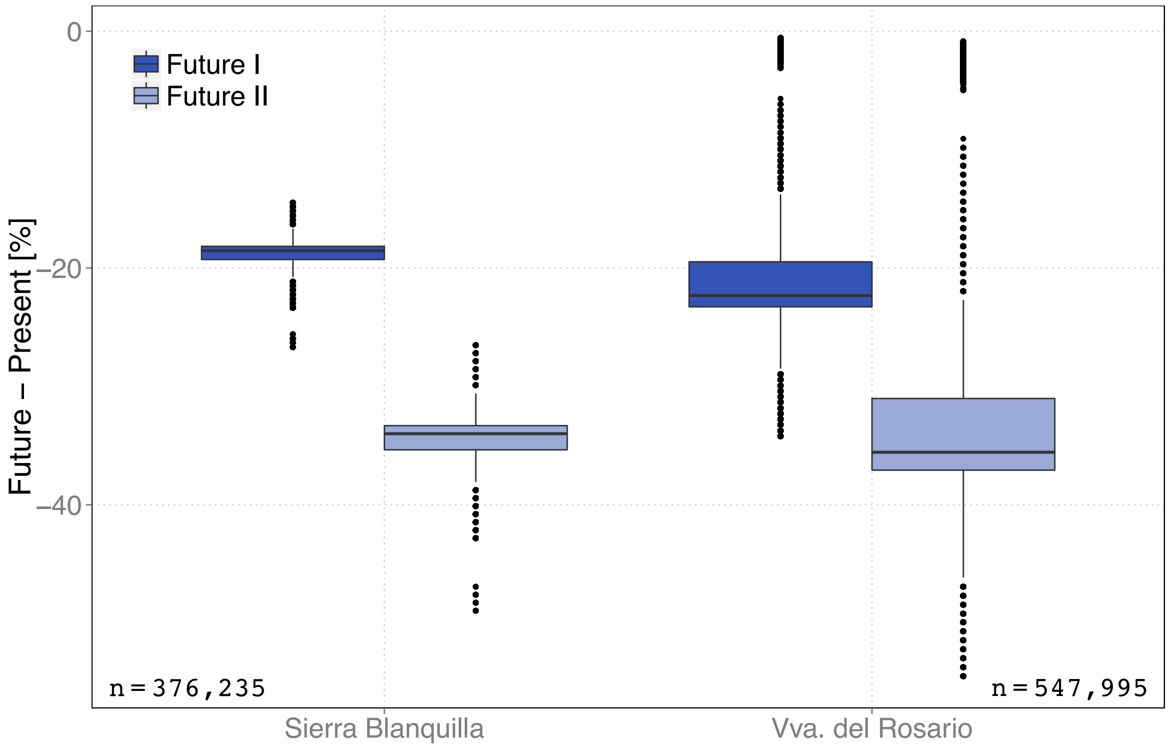

Figure 4.9: Boxplots showing the differences between future respectively remote future and present recharge rate rasters for the ensemble means of average years. Future I = future, Future II = remote future, n = number of data points and thus pixels.

The boxplots in Fig. 4.9 show the variability of spatial distribution of the differences between the recharge rates for the present and future time periods for the average years. For this the ensemble mean recharge rate raster of the present time period for the average years was subtracted from the ensemble mean recharge rate raster for the average years of the future respectively remote future. Basically, the maps displayed in Fig. 4.7 were subtracted from each other, and the maps displayed in Fig. 4.8 as well. The resulting rasters were exported as ASCII files and subsequently imported into *R* to draw the boxplots.

The displayed blue boxes of the plots contain 50 % of the data. The two whiskers mark the 25 % respectively 75 % quartile. The data points outside the range of box and whiskers are more than 1.5 times higher than the interquartile range and represent outliers. As can been seen from the plots for both study sites a large number of outliers occured, for Vva. del Rosario more than for Sierra Blanquilla. Also the range between minimum and maximum value is greater for Vva. del Rosario. Moreover, the box is greater for Vva. del Rosario and becomes larger for the remote future for both study sites, indicating a greater range of values.

For both study sites the boxplots indicate the decrease of recharge from present to future and remote future as the differences are becoming more negative.

5 Discussion

This chapter has been divided into three sections. First the reliability of the recharge estimations are discussed in terms of uncertainties of the method and related to available data sets. In the second part the results for the two study sites and the climate change scenarios are discussed and interpreted. The last section describes the impact of the study.

5.1 Reliability of the Recharge Estimations

To assess the reliability of the recharge estimations, the uncertainties related to the developed method and related to the utilized data are discussed.

5.1.1 Uncertainties related to the Method

The new approach is based on a simple water balance method which was combined with the existing GIS-based APLIS approach.
As Lerner *et al.* (1990) and Scanlon *et al.* (2002) explained, high errors in recharge estimates can be produced with the water balance method, since recharge is equated with the residual of the water balance equation. Consequently, errors in the estimation of precipitation and evapotranspiration accumulate in the determination of recharge. This error was reduced by calculating the soil routine with daily time steps. However, the soil routine remains a simple approach for calculating recharge and uncertainties of rainfall and evapotranspiration may still accumulate in the recharge estimations. Yet it should also be kept in mind that the method is not solely based on the soil water balance method, but it was combined with APLIS and thus with another method considering further parameters for recharge generation. On the other hand, the combination with another method also has the effect that the uncertainties of APLIS are included in the new extended approach. But considering the great advantages of APLIS in adding the spatial distribution of recharge into the calculations, this outweighs the effect. Moreover, APLIS is a well established method which has been successfully applied

in many different carbonate aquifers (Andreo *et al.*, 2008; Espinoza *et al.*, 2015; Farfán *et al.*, 2010; Gerner *et al.*, 2012; Guardiola-Albert *et al.*, 2014, 2015; Marín, 2009; Martos-Rosillo *et al.*, 2013; Zagana *et al.*, 2011).

Furthermore, uncertainty was related to the precipitation and evapotranspiration. As Pardo-Igúzquiza *et al.* (2012) stated precipitation and evapotranspiration can have great variations over space and time in mountainous Mediterranean karst terrains. But for the new method the same precipitation and evapotranspiration over the entire study sites was assumed. This is not realistic and the greater the extent of the considered study area, the greater will be the uncertainty related to this fact. However, considering the spatial distribution of rainfall and evapotranspiration would result in the necessity to use rasters as precipitation and evapotranspiration input. So far the method is calculating the recharge with single values for the entire catchment, which allows for fast calculations. The application of rasters would considerably increase computing time, but probably also enhance the accuracy of results. Aside from the assumption of a uniform precipitation and evapotranspiration distribution over the study area, the method also assumes the same maximum water storage capacity over the entire area. Therefore, no spatial variations were considered for this parameter either.

Another uncertainty was related to the type of recharge. The developed method only quantifies recharge generated by precipitation. Consequently, errors in recharge simulations can occur for study sites with indirect recharge taking place, e.g. through infiltration from river beds. This is the case in the Sierra Blanquilla study area where some recharge occurs by losing rivers (Barberá & Andreo, 2015).

Also not considered by the method is interception of precipitation by the vegetation. Pardo-Igúzquiza *et al.* (2012) also ignored interception in their approach arguing that this was included in the uncertainty range of precipitation and evapotranspiration. Due to the sparse vegetation in the study areas and the assumption of uniform precipitation and evapotranspiration in the new method, and hence the high uncertainty associated with that, the same assumption could be used. However, for areas with more vegetation effects of interception might have a greater influence.

Another point not taken into account are changes in land use in terms of simulating future groundwater recharge under climate change conditions.

Moreover, the structure of the new method with the application of a correction factor also allows for the simulation of recharge rates over 100 %, although this is unrealistic.

5.1.2 Uncertainties related to the Data Availability

Different uncertainties were associated with the input data for the method.

To calculate the maximum water storage capacity of the soil, porosity and soil depth data were needed as described in Chap. 3.2.3. No measured data were available for the porosity, and the great range of porosity values specified in literature for clayey soils (Blume *et al.*, 2010) yielded uncertainty. A mean value of porosity was taken for both study sites. The used soil depth data of the Harmonized World Soil Database (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012) had a low spatial resolution as can be seen from Fig. 3.4 displaying the soil depth in the study sites. The mean value of the occurring soil depths in each study area was taken for the entire catchment areas. Together with the porosity this resulted in a uniform pattern of the maximum soil water storage as described above. However even if these data were only available with a low spatial resolution they can be acquired globally and hence easily enable an application to a larger scale. But still the great range of porosity and the low spatial resolution of soil depth were a factor of uncertainty.

Considering the meteorological input data uncertainties arose due to incomplete time series. The time series of precipitation and temperature for Vva. del Rosario were complete and originated from one meteorological station. However, for the Sierra Blanquilla aquifer the time series were incomplete. For the precipitation time series data from a second meteorological station was used and gaps were filled by interpolation and assumption of no rain for two months. The temperature data were gap-filled using daily mean values. Completing data time series always involves some kind of uncertainty, and must thus be considered for Sierra Blanquilla. Yet, it should also be mentioned that the completion largely affected data for the year 2010 and was thereby at least not used for evaluation.

Moreover, the evaluation data for the Sierra Blanquilla study area were associated with an uncertainty since the data represented a net-discharge time series of two river gauging stations (Barberá & Andreo, 2015). In general, the results for Sierra Blanquilla were associated with a great uncertainty, due to insufficient data availability. Besides the fact that the evaluation data represented a net-discharge time series, there were just two years of discharge data available. Of these two years only one was useful, because the other one showed exceptionally high discharge. Moreover, the recharge area had to be calculated, which was done using solely the data of the average year.

The same applied to the correction factor. Just the data of one year could be used to calculate the factor. However, the method is based on a soil water balance. That method works for long time periods when the parameters are calculated from annual average values. But it does not work for single years when the change of storage does not equal zero. The longer the available time series, the more precise are the results. Thus, the uncertainties for the results of Sierra Blanquilla aquifer constituted of too short data time series, which in turn caused memory effects in the water balance and an uncertain determination of the recharge area and the correction factor. The relevance of long time series for the calculation of the recharge area is also shown by the influence of a variable recharge area, which is a specific karst characteristic (Hartmann *et al.*, 2013). Thus, no general recharge area is valid, instead it is changing with the climatic conditions. Also for Sierra Blanquilla aquifer the recharge area is different when calculated using the data of the wet year. Then, also the extremely high discharge rate of over 100 % would not occur for the wet year. However, for that case the calculations would also not be based on average conditions. Considering all these factors the results for Sierra Blanquilla should not be overrated.

Climate models are associated with large uncertainties (Portmann *et al.*, 2013), which is reflected in the reliability of the recharge simulations results with the climate scenario data. As Portmann *et al.* (2013) state the use of five different global climate models enlarges the range of uncertainty, but it also enables the researcher to cover a broad range of different scenarios of future temperature and precipitation evolution. They also emphasize that only presenting the ensemble mean of results without considering the individual results for the different climate model data, may result in a wrong assessment of the risks which are associated with climate change. To prevent this, also the results for the individual models were viewed more closely, even though the ensemble mean was used for presentation. Moreover, the minimum and maximum values showed the range of results of the different models.

Despite all these uncertainties there are reasons to trust the results, as can be concluded from the following discussion of results.

5.2 Interpretation of the Results

This section is subdivided into three subsections. First the results of Vva. del Rosario study area are discussed, afterwards the results for Sierra Blanquilla and the last part is investigating the results of the climate scenario data.

5.2.1 Villanueva del Rosario

The results of the evaluation indicated a successful application of the method in the Vva. del Rosario study area, since similar rates for recharge and observed spring discharge were obtained. Consequently, it could be concluded that reliable recharge estimation results were calculated with the new method. Like that also the results for the available measured data time series showed reasonable recharge estimations.
The results of the recharge simulation made clear that APLIS is underestimating recharge in wet years and overestimating recharge in dry years compared to the new method. This was also observed by Hartmann *et al.* (2014b) contrasting results of VarKarst and APLIS. Hence, the consideration of temporal variability of meteorological data in the recharge estimation method led to more realistic results and revealed a great variability of recharge between wet and dry years. The results obtained with the new method were still underestimating recharge in wet years and overestimating recharge in dry years. However, the results were much closer to the observed values than the mere APLIS recharge estimates.
Furthermore, the results emphasized the relevance of considering the temporal distribution of rainfall and evapotranspiration in recharge simulations. Hence, these confirm the finding of Guardiola-Albert *et al.* (2014) that average recharge estimates over long time periods are underestimating recharge during wet periods. And more general, that recharge estimates over long periods should be obtained by summing up the results of shorter time intervals (Lerner *et al.*, 1990).

The reason for the influence of the temporal pattern of precipitation was shown by the plotted time series of recharge and precipitation for selected years (Fig. 4.1, 4.2). During the years the rainfall events with high intensities generated more recharge than more evenly distributed and smaller recharge events. Rainfall with a high-intensity can quickly fill up the soil storage of the soil routine, exceed the threshold of maximum soil water storage and generate recharge. If many small rainfall events occur, the soil storage gets filled up step by step, but water is also constantly lost to evapotranspiration and the threshold may not be reached. In contrast, if one great recharge event provides enough water to exceed the maximum soil water storage, a great amount of water can directly percolate down to the groundwater without being lost to evapotranspiration. If precipitation is summarized over a longer time period, these important peaks in precipitation are smoothed out (Scanlon *et al.*, 2002) and cannot result in recharge peaks. This explains why years with similar precipitation amounts resulted in very different amounts of recharge when temporal rainfall distribution was considered. Consequently, these results corresponded with the outcomes of Ries *et al.* (2015) and de Vries & Simmers (2002) who stated that in semi-arid areas the greatest amount of recharge is generated during high-intensity rainfall events.

The relationship between precipitation and recharge was investigated with the same plots (Fig. 4.3) as in Martos-Rosillo *et al.* (2015). They summarized results of recharge estimations with different methods in the Betic Cordillera. Like in their results, also in this thesis a non-linear relationship was found between recharge and recharge rate. With increasing recharge a stabilization of the recharge rate could be observed. However, the value lay somewhat higher at a rate between 60 and 70 %, whereas in the study of Martos-Rosillo *et al.* (2015) it stabilized at a value close to 60 %. Also a linear relationship was found between the amount of precipitation and recharge. Even though the regression in Martos-Rosillo *et al.* (2015) was increasing slightly greater than in this study. Furthermore, the results of this thesis showed a non-linear relationship between precipitation and recharge rate. Although Martos-Rosillo *et al.* (2015) did not fit any regression to that specific plot, it is obviously non-linear. Consequently, even though differences could be observed between the results of their study and of this thesis, it followed that the results of this thesis were consistent with the study, which enhanced the reliability of the new method.

A linear relation between the amount of precipitation and recharge was also found for other karst aquifers by Lerner *et al.* (1990) and Touhami *et al.* (2013). This presents a very simple approach for rough estimations of recharge. If this relation is known for an aquifer, it can be applied to different precipitation sums, for instance to get an idea of future recharge under decreasing precipitation. However, this is not very precise, but it is still conspicuous since it occurred in different studies. The results also showed that the influence of the temporal pattern of rainfall could outweigh this linear effect, because also years with less precipitation generated more recharge if more high-intensity rainfall events occurred.

Moreover, the non-linear relationship between precipitation and recharge rate was also found by Martínez-Santos & Andreu (2010) and Hartmann *et al.* (2014b). Sim-

ilar to the results in Hartmann *et al.* (2014b) a sharp increase in the regression for small annual rainfall sums could be observed. Consequently, small decreases in already low rainfall amounts will cause a stronger decrease in recharge than small decreases in higher rainfall sums. And more general, a decrease in precipitation, as predicted for climate change (Treidel *et al.*, 2011) will have a stronger effect on recharge than an increase.
The described results of Hartmann *et al.* (2014b) were produced applying the process-based karst model VarKarst. Thus, the results of the new method were comparable to the results of a process-based karst model. However, it has to be noted that they also investigated the Vva. del Rosario aquifer using the same meteorological data for the same hydrolgical years.

Martos-Rosillo *et al.* (2015) concluded that for precipitation sums smaller than 200 to 300 mm recharge can be negligible, and Hartmann *et al.* (2014b) found a threshold of 250 mm. This is both consistent with the results of this thesis. Also Scanlon *et al.* (2006) stated in their study on recharge in (semi-)arid regions that almost no recharge is generated for annual precipitation sums smaller than 200 mm.
Furthermore, Martos-Rosillo *et al.* (2015) summarized in their study a mean recharge rate of 38 % with a range between 4 and 67 % for several aquifers in the Betic Cordillera. Andreo *et al.* (2008) stated a mean recharge rate of 44 % calculated with different methods for eight aquifers also located in the Betic Cordillera. The rates in that study ranged between 33 to 55 % for the different aquifers. However, they did not include aquifers of the drier southeastern part of the Betic Cordillera as in Martos-Rosillo *et al.* (2015). That could explain the lower mean rate in that study and the greater range for different aquifers. In this thesis a mean recharge rate of 39 % was found for the Vva. del Rosario study area. This rate lay in the range of rates reported in the mentioned studies.

The spatial distribution of the recharge rates (Fig. 4.5) distinguished the strongest influence of the APLIS parameters lithology, infiltration landform, and correction coefficient of recharge on the pattern of recharge distribution. Areas with low and moderate recharge rates could clearly be assigned to the type of geology, namely Cretaceous-Tertiary and Triassic clays, Quaternary sands and gravels respectively. For the parts with high recharge rates in Jurassic limestone and dolostone, a strong influence of the infiltration landform parameter could be identified. Thus the parameters lithology and infiltration landform could be identified as the most influential on the recharge pattern;

together with the correction coefficient of recharge as this one is closely connected to the lithology. These parameters also overlay effects of altitude parameter. No influence of the altitude on the spatial recharge pattern could be found as stated in Hartmann *et al.* (2014b). This would probably be different if spatially distributed rainfall and evapotranspiration would be considered. Then rainfall would increase with increasing height, and evapotranspiration decrease due to temperature decrease and consequently higher recharge rates could be expected in high altitudes. The findings are related to the weighting of the input parameters in the APLIS equation. The lithology and infiltration landform parameter are multiplied by three respectively two. Thereby their influence on recharge generation is greater than that of the remaining variables (Andreo *et al.*, 2008). This became visible in the spatial distribution of recharge results. The spatial pattern of recharge also revealed that rates over 100 % occurred. At least in the Vva. del Rosario study area only small parts were affected. These were the areas of the swallow holes which were represented by a highly developed infiltration landform in the APLIS input.

5.2.2 Sierra Blanquilla

As described in Chap. 5.1.2 the results of Sierra Blanquilla were associated with a great uncertainty due to the few available data sets. Hence, no sufficient evaluation could be carried out for that study site. These uncertainties also explain the high rates for recharge and discharge with partially over 100 %. Hence, also the observed mean recharge rate for Sierra Blanquilla (85 %) was high and lay outside the ranges reported in literature (Andreo *et al.*, 2008; Martos-Rosillo *et al.*, 2015). That the average year lay in the range stated by Martos-Rosillo *et al.* (2015) was no surprise, since it equaled the original APLIS rate and the result of recharge estimations for the Sierra Blanquilla aquifer using the APLIS method was also included in the study of Martos-Rosillo *et al.* (2015).
Although only a short time series was available the great influence of the temporal rainfall pattern on the recharge generation could also be demonstrated in the Sierra Blanquilla aquifer.

Regarding the spatial distribution of recharge it was observed that it was not as diverse as for the Vva. del Rosario study site. This was due to the APLIS input maps which do not include a great range of classes for the different variables (Fig. A.3, A.4). It is conspicuous that Cretaceous and Triassic geologies which generated the lowest recharge

rates in the Vva. del Rosario aquifer were not included in the APLIS raster for Sierra Blanquilla, as they were for Vva. del Rosario. This explains why no low recharge rates were present in the Sierra Blanquilla study site. The contained lithology types comprise solely Jurassic limestone and dolostone. As in the Vva. del Rosario study area the influence of lithology on the recharge pattern could be identified; although less obvious because of the missing diversity of different lithology types. Opposed to this, the strong influence of the infiltration landform parameter could also be clearly determined. The parameter of the correction coefficient of recharge is the same over the entire study site, due to missing impermeable lithology types. Thus, the degree of influence could not be clearly distinguished. The strong influence of lithology and infiltration landform is once again related to the greater weighting of these variables in the APLIS equation (Andreo *et al.*, 2008).
Large areas generated recharge rates over 100 % during the wet year. On the one hand this is the effect of the correction factor which enables to simulate such high recharge rates, but on the other hand such results were owed to the high uncertainties in the available data for Sierra Blanquilla.

5.2.3 Climate Scenario Data

For the application of climate scenario data two different ways of combining the soil routine output for the climate data with the correction factor (Chap. 3.5) were performed. One approach was to use the correction factor which had been calculated with the time series of measured meteorological data, also for the recharge simulations with the modeled climate data. However this resulted in a great underestimation of recharge as can be seen from the results in the Appendix (Tab. A.1). Only for the Sierra Blanquilla aquifer the results seemed more appropriate. Yet, due the described sparse data availability for this area and the associated uncertainty the results were not reliable. Hence, this approach was rejected.
The other approach was to calculate a separate correction factor for each model. These results showed a general decrease in groundwater recharge in the future for the average years for all five climate models. Just for the wet years not all climate data resulted in a decrease. For the dry years simulated recharge was zero for the future time periods. Since there was already zero recharge simulated during the present time period, except for one model it cannot really be called a decrease.

The decrease in recharge is consistent with the results of other studies which investigated groundwater recharge in karst aquifers under changing climatic conditions (Brouyére *et al.*, 2004; Hao *et al.*, 2006; Loáiciga *et al.*, 2000). Also the study of Portmann *et al.* (2013) found a decrease in groundwater recharge for (semi-)arid areas. They did not specifically simulate karst aquifers but applied a global hydrological model. They applied the same five climate models as have been used in this thesis and also found a decrease in recharge for all five models. They did not differentiate extremely wet and dry years. However, they also emphasized the great uncertainty involved with the climate models, which also becomes visible comparing the global spatial distribution of recharge for the different models in their study. Yet, for the Mediterranean all models indicated a decrease in recharge.
Hartmann *et al.* (2012) found in their study a decrease in water availability of 15 to 30 % for the remote future (2068-2098). In this thesis the amount of recharge for the average years was decreasing by 80 % on average for the remote future for Vva. del Rosario and by 77 % for Sierra Blanquilla. This exhibits a great difference to the results of Hartmann *et al.* (2012) and indicates an overestimation of recharge decrease. For the near future (2012-2051) the variability in their results of different models and climate change scenarios was too high to specify a definite result. For the results with climate scenario data in this thesis the variability in results was similarly high for both future time periods. However, for the average years they all showed a decrease in recharge, although with different degrees of decrease.
Summarized it can be concluded that all results for the average years suggested a decrease in recharge in the future, which is consistent with other mentioned studies. However, great uncertainty was associated with the extent of decrease. The dry years showed consistent results over all models, resulting in zero recharge. For the wet years not all models suggested a decrease and thus a future decrease in recharge for extremely wet years could not be predicted with certainty.

Regarding the present time period it became obvious that the annual precipitation sums of the present time period of the climate models were lower than the measured annual rainfall sums for both study sites. This indicated that the climate models were simulating too little precipitation. Consequently, it must be assumed that also for both future time periods the amount of precipitation might be underestimated. This could explain the overestimation of recharge decrease compared to Hartmann *et al.* (2012). Moreover, compared to the results of the measured data, recharge was overestimated in the wet years and underestimated in the dry years. The very little recharge for the

dry years can be explained with the low modeled precipitation of the climate models. A reason for the high recharge rates in the wet years were the correction factors. These were higher for the climate model data than for measured data (Tab. 4.4). The correction factor is the quotient of the APLIS recharge and soil routine recharge. Consequently, for the calculations with the climate data, the recharge of APLIS must have been considerably higher than the recharge from the soil routine. Which in turn can be explained again by the little simulated rainfall. The precipitation amount was not enough to exceed the threshold of the maximum soil water storage capacity. Also the effect of the temporal rainfall pattern might have influenced the great differences. Of course the high correction factors influenced all results of the climate models and not just those of the wet years. Yet, there the effect became most visible.
Furthermore, for the results with the climate scenario data it could also be observed that years with very similar rainfall amounts simulated greatly different recharge amounts. Thus, once again the influence of the temporal rainfall distribution on recharge generation became evident.

The presented boxplots (Fig. 4.9) indicated that the variability of spatial distribution of recharge rate differences was greater between remote future and present, than between future and present. This is explained by the fact that the values of recharge rates for the remote future differed greater from the present than the future rates from the present rates. Hence, a greater range of values for the differences was produced which was reflected in the range of the boxplots. Moreover, the range of the boxplots was greater for Vva. del Rosario than for Sierra Blanquilla. This was attributed to the greater spatial variability of recharge rates for Vva. del Rosario than for Sierra Blanquilla. This resulted from the APLIS rate raster which shows a greater range of recharge rates values for Vva. del Rosario than for Sierra Blanquilla. This in turn is dependent on the different characteristics of the APLIS input variables which show greater variability for Vva. del Rosario than for Sierra Blanquilla (Fig. A.1-A.4).

5.3 Impact of the study

As outlined in the introduction the groundwater of the carbonate aquifers in southern Spain is of great importance for the water supply in Andalusia. Especially during drought periods (Martos-Rosillo *et al.*, 2015). Additionally the Mediterranean was identified as a region particularly vulnerable to future climate change (Giorgi & Lionello, 2008). Hence, tools are required to assess groundwater recharge for water resource planning. However, most of the developed tools for recharge estimation are complex and need a lot of data and time to set them up. To use recharge estimation methods more regularly for groundwater management, it is necessary to develop simple and easy-to-use tools for spatial and temporal recharge estimations (Dripps & Bradbury, 2007).

The simple method developed here showed reliable results for recharge estimations for the Vva. del Rosario study area. Other more complex hydrological models like the process-based karst model VarKarst (Hartmann *et al.*, 2013) or the ZOODRM (Mansour & Hughes, 2004) and Visual Balan model (Samper *et al.*, 1999) would probably lead to more precise results. They consider more different processes in the recharge generation and hence provide more differentiated results. However, these models are also more complicated in their application and require more input data. Moreover, often data is required which is difficult to obtain, and might therefore limit the model implementation. The new method developed in this thesis might be less precise in the recharge estimates. However, it is much easier to apply, using input data which is relatively easy to obtain and being based on an method that has established itself through several successful applications (Andreo *et al.*, 2008; Espinoza *et al.*, 2015; Farfán *et al.*, 2010; Gerner *et al.*, 2012; Guardiola-Albert *et al.*, 2014, 2015; Marín, 2009; Martos-Rosillo *et al.*, 2013; Zagana *et al.*, 2011). Consequently, the new method has a higher relevance for water management questions than complex process-based karst models because it is easy to use.
It presents a simple tool which can be used by those responsible for planning water resources to quantify and assess groundwater recharge and develop sustainable management plans. Due to the temporal resolution on a daily basis, it is not only possible to quantify recharge on an annual scale, but also on a monthly or seasonal scale. Thus, the effects of the great inter-annual variability of rainfall in the Mediterranean (Guardiola-Albert *et al.*, 2014) are considered and it is possible to look at individual time slots.
Moreover, it can be used to assess the evolution of groundwater recharge under climate change conditions and thus enable planning to adapt to projected changes.

6 Conclusion

The thesis presented the successful implementation of a new method to quantify groundwater recharge in a Mediterranean karst region. The existing APLIS method which estimates spatially distributed annual average recharge was extended with a simple soil routine to include temporally distributed precipitation and evapotranspiration and to facilitate time dynamic recharge estimations. The new method was applied in two study areas in southern Spain. Aside from applying measured meteorological data, also climate scenario data were used.

The results show that it was possible to integrate the temporal variability of precipitation and evapotranspiration in recharge estimations in a simple way under present data availability. An easy-to-use tool for the application in water management questions was developed with a good balance between the degree of complexity of the approach and the accuracy of the results.

In contrast, the research question whether it is possible to transfer the new method to further catchments in Andalusia could not be finally clarified. The reason was that not enough data sets were available for a thorough evaluation and application to another study site. The available results for the average year indicated that it is possible, but it did not become clear how results would look like for extreme dry and wet years. For the climate scenario data the results looked similar for both study sites. However, this does not change the fact that the Sierra Blanquilla aquifer could not be thoroughly evaluated using observed data. Thus, there are indications that it is possible to transfer the approach to other study sites, and nothing disproves this assumption. However, more data is needed to fully prove the transferability to further catchments.

The consequences of the consideration of temporal variability of meteorological data on the estimated recharge could clearly be recognized. Whereas the existing APLIS method is underestimating recharge in wet years and overestimating recharge in dry years, the new method was able to reflect these differences in climatic conditions much better. Hence, more recharge was calculated for wet years and less for dry years. This is due to the great influence of the temporal rainfall pattern on recharge generation. This fact is not considered when calculating the recharge solely from rainfall sums over longer periods. However, due to the extension of APLIS with the soil routine, the temporal pattern is included in the recharge simulations and led to more realistic results.

It was also investigated whether this new method can be used to assess future groundwater recharge. The resulting decrease in the future was consistent with other studies. Thus, it can be concluded that the approach is capable of estimating recharge under climate change conditions. However, application of climate scenario data is always associated with a great range of uncertainty. Even though the results for all model data suggested a decrease in future recharge for the average years, it did not become clear to which extent the decrease will appear. Furthermore, for the wet years no clear decrease of recharge for the future could be distinguished. Therefore estimations of future recharge strongly depend on the used climate scenario model and involve a great range of uncertainty.

The discussion of the results also revealed possible improvements of the method which would further enhance the results. A great advancement would be the consideration of spatially distributed rainfall and evapotranspiration, instead of assuming a uniform pattern over the entire study areas. However, this would also require the use of rasters and thus increase computing time. Furthermore, the determination of the maximum water storage capacity of the soil could be refined. The porosity value was obtained from a specified range for clay. An uncertainty analysis could be performed to analyze the effect of different porosity values. The soil depth was considered by taking the mean value of occurring soil depths for the entire study site. However, the Python code could be extended in a way that different types of soil depths are considered. For instance by calculating different soil water balances for each depth. Also using soil depth data with a higher resolution would lead to more precise results. Yet, the clear advantage of the used soil data is the global availability. Regarding the use for simulation of recharge under climate change conditions the consideration of land use change might improve the results.
To finally apply the method to a larger scale would require more catchment analyses. Consequently, more data is needed for the application and the evaluation to further confirm the method. Nevertheless, this thesis shows highly promising results and suggests a simple tool for practical use in water management.

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A Appendix

Table A.1: Results of the recharge simulations for the study sites Vva. del Rosario and Sierra Blanquilla using the same correction factor of the measured data for all climate model data. Displayed are the ensemble means of all five climate models for the present time period. P: Precipitation, R: Recharge, RR: Recharge rate. The results of the measured data used for evaluation are also displayed for comparison.

		P [mm]	**R [mm]**	**RR [%]**	**Year**
Rosario		**Measured data**			
	wet	932.2	603.4	64.7	2008/2009
	dry	642.2	209.6	32.6	2006/2007
	average	752.4	350.8	46.6	2006-2009
		Ensemble mean climate models present (1989-2009)			
	wet	834.8	332	38.5	na
	dry	312.5	8.8	2.3	na
	average	552.4	113.7	20.5	na
Blanquilla		**Measured data**			
	wet	883.9	864.7	97.8	2008/2009
	dry	-	-	-	-
	average	834	465.7	55.8	2007/2008
		Ensemble mean climate models present (1989-2009)			
	wet	913.1	635.8	68.3	na
	dry	324.5	2.7	0.6	na
	average	596.5	240.4	40.2	na

Table A.2: Results of recharge simulations for individual climate models for Vva. del Rosario using a separate correction factor for each model. P: Precipitation, R: Recharge, RR: Recharge rate, Present (1989-2009), Future I = Future (2039-2059), Future II = Remote future (2079-2099). Highlighted are the results of the model with an increase in recharge.

		P [mm]	R [mm]	RR [%]	P [mm]	R [mm]	RR [%]
			GFDL			**HAD**	
Present	max	659.2	384.5	58.3	831.5	801.1	96.3
	min	332.8	0.0	0.0	359.3	0.0	0.0
	average	517.9	241.4	46.6	589.9	275.0	46.6
Future I	max	686.1	620.9	90.5	961.9	860.5	89.5
	min	216.6	0.0	0.0	261.8	0.0	0.0
	average	417.9	142.2	34.0	439.5	125.6	28.6
Future II	max	699.7	560.3	80.1	619.4	413.8	66.8
	min	164.1	0.0	0.0	122.4	0.0	0.0
	average	314.2	62.5	19.9	375.1	62.8	16.8
			IPSL			**MIROC**	
Present	max	944.0	818.5	86.7	946.4	1112.1	117.5
	min	222.2	0.0	0.0	392.5	128.8	32.8
	average	515.2	240.2	46.6	562.8	262.4	46.6
Future I	max	788.1	590.8	75.0	580.9	406.6	70.0
	min	218.2	0.0	0.0	277.3	0.0	0.0
	average	470.9	164.9	35.0	427.9	36.8	8.6
Future II	max	602.3	382.7	63.5	536.9	0.0	0.0
	min	55.8	0.0	0.0	227.6	0.0	0.0
	average	285.5	57.0	20.0	330.6	15.5	4.7
			NOR				
Present	max	792.7	601.2	75.9			
	min	255.9	0.0	0.0			
	average	576.2	268.6	46.6			
Future I	max	806.1	556.3	69.0			
	min	329.1	0.0	0.0			
	average	519.3	141.5	27.2			
Future II	max	792.3	399.5	50.4			
	min	146.6	0.0	0.0			
	average	359.3	47.1	13.1			

Table A.3: Results of recharge simulations for individual climate models for Sierra Blanquilla using a separate correction factor for each model. P: Precipitation, R: Recharge, RR: Recharge rate, Present (1989-2009), Future I = Future (2039-2059), Future II = Remote future (2079-2099). Highlighted are the results of the model with an increase in recharge.

		P [mm]	R [mm]	RR [%]	P [mm]	R [mm]	RR [%]
			GFDL			**HAD**	
Present	max	711.2	653.1	91.8	934.5	871.7	93.3
	min	315.6	0.0	0.0	384.5	0.0	0.0
	average	556.0	310.5	55.8	641.4	358.2	55.8
Future I	max	734.3	632.6	86.2	1070.4	1038.4	97.0
	min	222.3	0.0	0.0	255.3	0.0	0.0
	average	446.3	191.8	43.0	467.9	188.2	40.2
Future II	max	748.4	572.8	76.5	671.3	439.9	65.5
	min	190.1	0.0	0.0	131.9	0.0	0.0
	average	332.8	80.7	24.2	405.0	111.2	27.5
			IPSL			**MIROC**	
Present	max	1038.8	1044.2	100.5	1013.8	1079.6	106.5
	min	229.2	0.0	0.0	426.6	21.6	5.1
	average	558.7	312.0	55.8	608.5	339.8	55.8
Future I	max	869.4	714.7	82.2	657.4	471.7	71.7
	min	200.3	0.0	0.0	279.4	0.0	0.0
	average	502.5	231.0	46.0	452.9	92.5	20.4
Future II	max	584.9	410.6	70.2	535.4	82.8	15.5
	min	57.0	0.0	0.0	224.4	0.0	0.0
	average	297.4	73.8	24.8	347.2	40.5	11.7
			NOR				
Present	max	867.1	723.0	83.4			
	min	266.7	0.0	0.0			
	average	618.0	345.1	55.8			
Future I	max	860.6	628.7	73.1			
	min	319.8	0.0	0.0			
	average	542.5	197.9	36.5			
Future II	max	811.6	454.9	56.0			
	min	148.7	0.0	0.0			
	average	367.5	74.2	20.2			

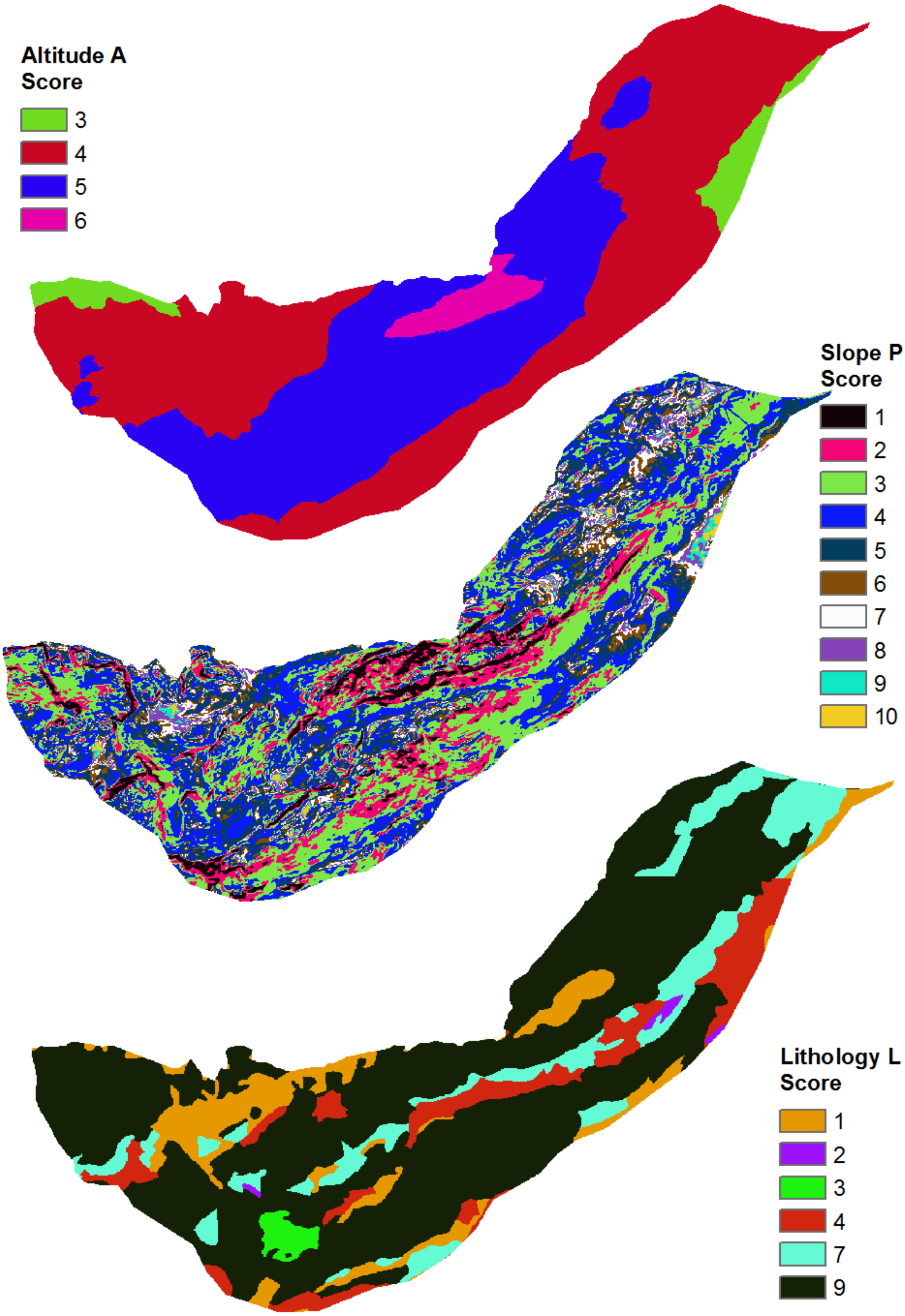

Figure A.1: Maps of the APLIS input variables altitude, slope, and lithology for Vva. del Rosario. Scores are explained in Tab. 3.3.

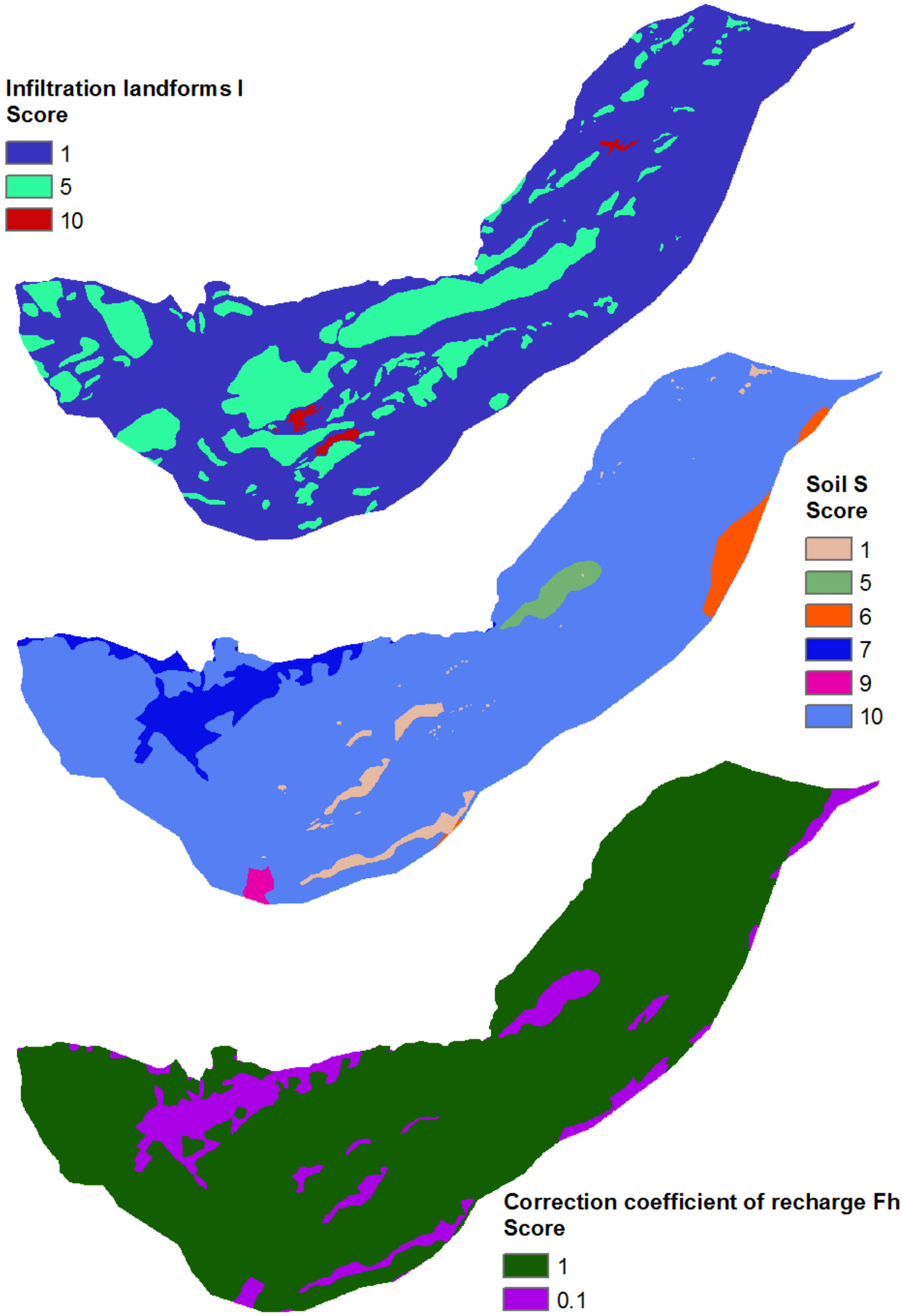

Figure A.2: Maps of the APLIS input variables infiltration landforms, soil, and correction coefficient of recharge for Vva. del Rosario. Scores are explained in Tab. 3.3.

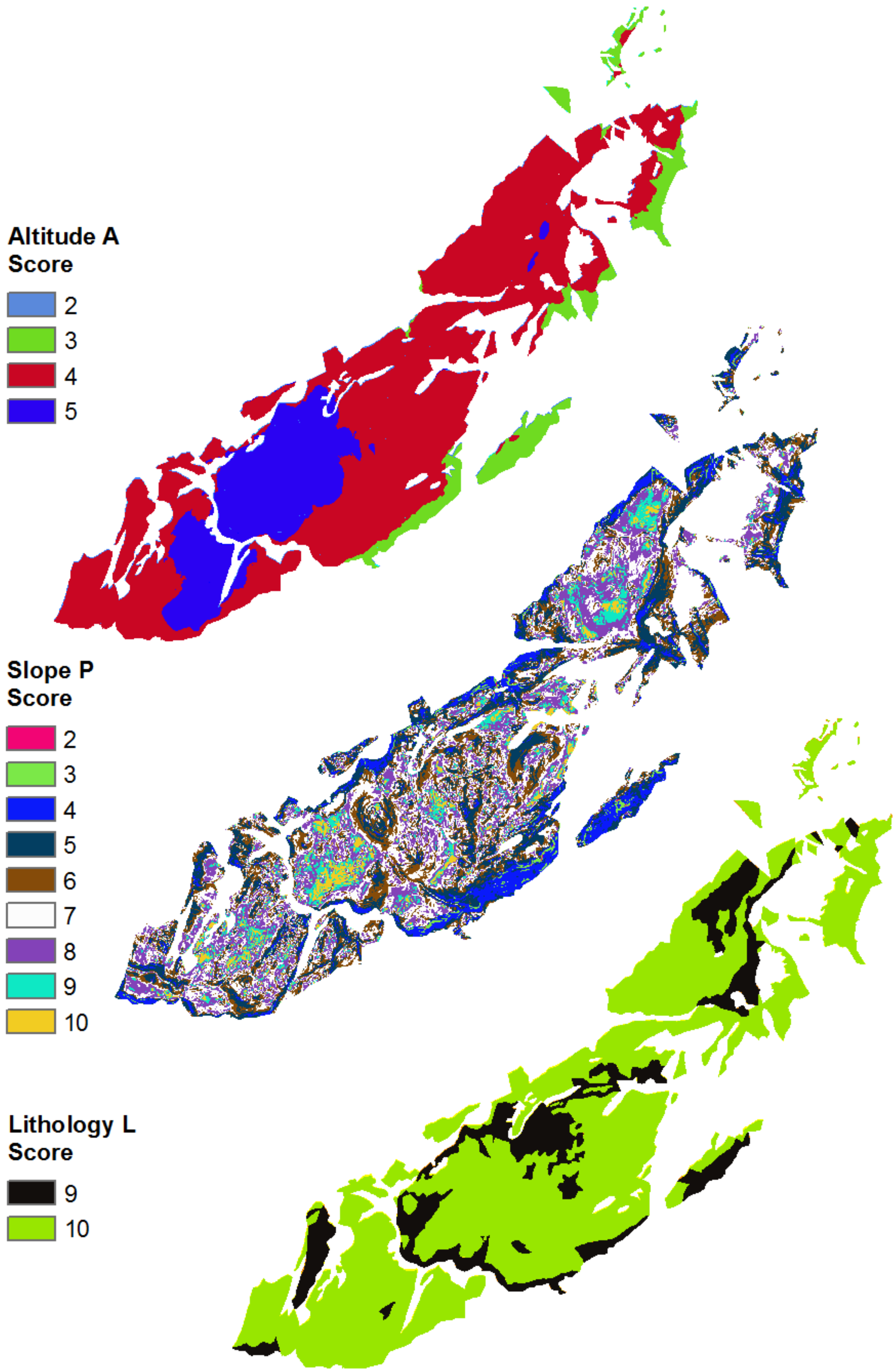

Figure A.3: Maps of the APLIS input variables altitude, slope, and lithology for Sierra Blanquilla. Scores are explained in Tab. 3.3.

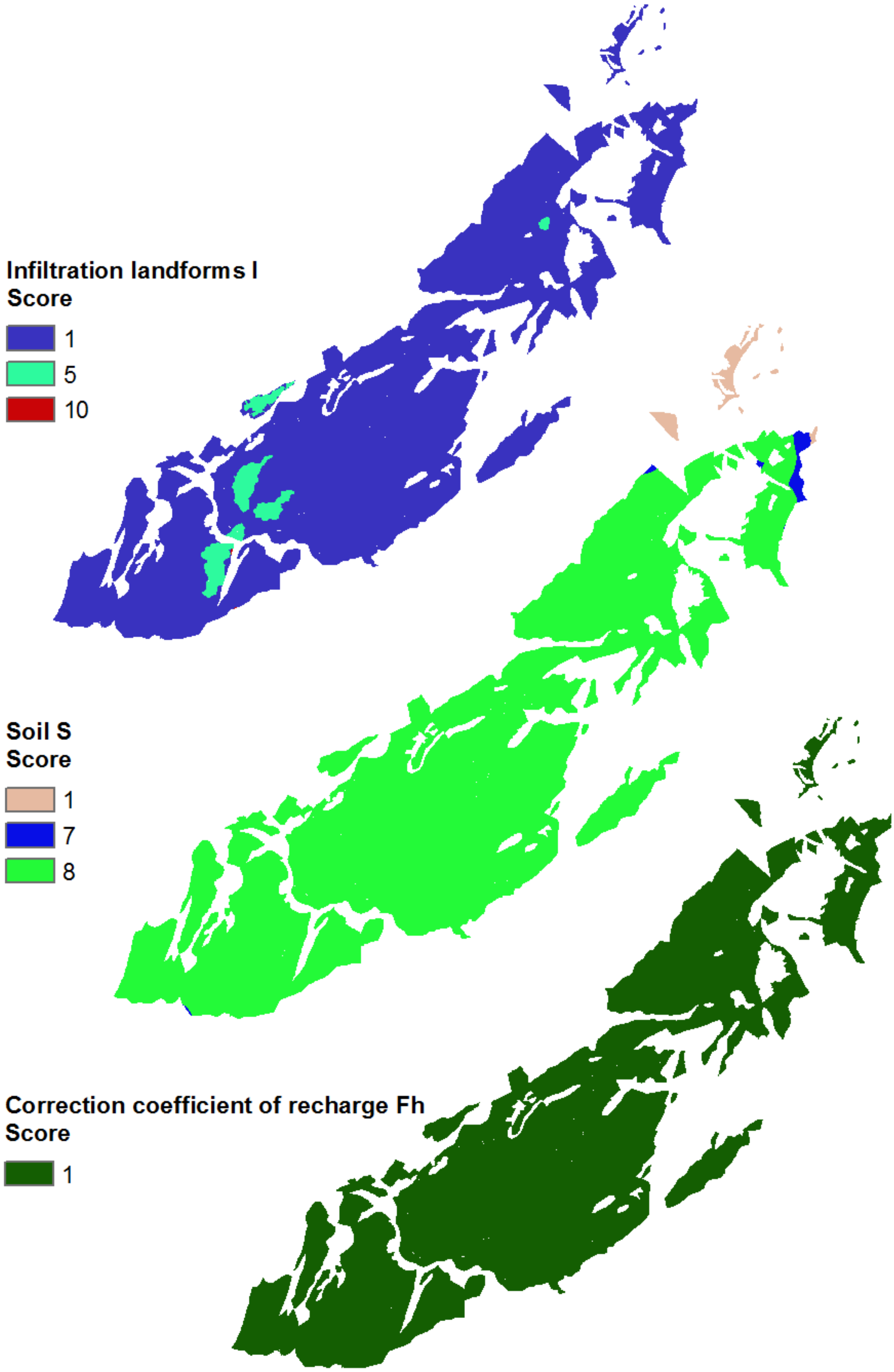

Figure A.4: Maps of the APLIS input variables infiltration landforms, soil, and correction coefficient of recharge for Sierra Blanquilla. Scores are explained in Tab. 3.3.

Ehrenwörtliche Erklärung:

Hiermit erkläre ich, dass die Arbeit selbstständig und nur unter Verwendung der angegebenen Hilfsmittel angefertigt wurde.

Freiburg im Breisgau, 15. September 2015

Unterschrift