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# Parameterization and quantification of recharge in crystalline fractured bedrocks in Galicia-Costa (NW Spain)

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## Abstract

Quantification of groundwater recharge in crystalline rocks presents great difficulties due to high heterogeneity. Traditionally these rocks have been considered with very low permeability, and their groundwater resources have been usually neglected, although they can have local importance when the bedrock presents a net of fractures well developed. Current European Water Framework Directive requires an efficient management of all groundwater resources, which begins with a proper knowledge of the aquifer and accurate recharge estimation. In this study, an assessment of groundwater resources in the Spanish hydrologic district of Galicia-Costa, with a geology mainly dominated by granitic and metasedimentaty rocks, was carried out. A water-balance modeling approach was used for estimating recharge rates in nine pilot catchments representatives of both geologic materials, and results were cross-validated with an independent technique as Chloride mass balance (CMB). A relation among groundwater recharge and total precipitation according to two different logistic curves was found for granites and metasedimentary rocks, which allows the parameterization of recharge by means of few hydrogeological parameters. Total groundwater resources in Galicia-Costa were estimated in 4427 $Hm^3 yr^{-1}$. An analysis of spatial and temporal variability of recharge was also carried out.


## 1 Introduction

Groundwater is an important source of potable drinking water. Worldwide 50 % of municipal water supplies come from groundwater. In general, groundwater is particularly important as a source of drinking water for rural and dispersed population (Fornés et al., 2005).

Since the 1950s and due to advances in drilling technology, the groundwater use has experienced a remarkable growth, primarily as result of initiatives taken by thousands of individual users, farmers and small municipalities. The public sector has





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rarely participated in the planning, administration or control of these developments (Hernandez-Mora et al., 2001). It is significant that, in spite of its importance, groundwater continues to be a largely misunderstood and often neglected resource, and some southern European countries lack good groundwater quality and quantity monitoring systems (Hernandez-Mora et al., 2001). If the prevailing anarchy continues, serious problems may appear in the mid or long-term. Some are already well documented, although at a lesser scale, and are usually related to water table depletion, groundwater quality degradation, land subsidence, or ecological impacts on aquatic ecosystems (Llamas and Martínez-Santos, 2005). Groundwater depletion is especially problematic in the case of shallow aquifers where directly the drying up of shallow wells can occur, mainly affecting the water supply of the less resourceful population sector.

After the approval of the European Water Framework Directive (WFD), the different Water Agencies are required to reach a good quantitative and qualitative conservation condition of groundwater and surface water bodies (European Commission, 2000). For that aim, an initial characterization and knowledge of actual renewable resources is needed, included groundwater resources. Quantification of the rate of groundwater recharge is a basic prerequisite for efficient groundwater resource management. However, the rate of aquifer recharge is one of the most difficult components to measure when evaluating ground water resources (Sophocleous, 1991). In that sense, the development of new river basin management plans in accordance with the requirements of the WFD is a challenge for European Water Agencies.

The hydrologic district of Galicia-Costa is one of de 16 districts in which the Spanish water administration is divided. It covers all the watersheds completely located inside the Autonomous Region of Galicia (NW of Spain). In this district more than a quarter of total population use groundwater by means of private water supply facilities, especially in rural areas (Romay and Gañete, 2007). This use of groundwater occurs on the fringes of the public water supply, by means of individual or communal private wells and water collectings. According the Spanish Geologic Survey (IGME) more than 300 000 wells exist in Galicia (Navarro Alvargonzález et al., 1993). All these





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groundwater abstractions contrast with the low study and knowledge of the groundwater in Galicia. The granitic and metamorphic rocks which dominate the area of Galicia-Costa have been traditionally considered almost impervious or with very low permeability, and their groundwater resources have been usually neglected in planning and water management. However, shallow aquifers with local importance can be developed by weathering and fracturing of the bedrock and groundwater can become an important and volumetrically significant water store (Neal and Kirchner, 2000). Several works carried out in different sites in North Portugal with similar geologic and climatic characteristics and using different methodologies (water balance, chloride mass balance, flow hydrograph decomposition) estimate the groundwater recharge in a range of 5 % to 31 % of precipitation (Alencoão et al., 2000; Lima and Silva, 1995; Martins Carbalho et al., 2000; Pereira, 2000). The few studies carried out in Galicia show that although groundwater recharge rate is low, it is not negligible, especially taking account the high precipitation rate in this region (900–2500 $\mathrm{mm\,yr^{-1}}$). In a site study on granitic terrains the recharge was estimated by means of water balance model in 8.8 % of annual precipitation (Samper et al., 1997, 1999; Soriano and Samper, 2000). With the same methodology, Raposo et al. (2010) estimates an average recharge of 13.6 % of annual precipitation in five granitic catchments in Galicia-Costa. This wide range of recharge rates makes it difficult a regional characterization and quantification of groundwater resources. A new approach is needed to propose a regional recharge rate, different than the classical linear relationship recharge-precipitation.

Aquifers with similar characteristics to Galician ones, developed on fractured crystalline bedrocks, are relatively frequent along the Atlantic Europe, in Brittany (France), Wales and Cornwall (UK) and Ireland, besides in the neighboring North Portugal. All these regions are characterized by high precipitation conditions and Hercynian bedrocks, and a traditional use of shallow groundwater (Environment Agency, 2005; Robins, 2009).

An accurate aquifer recharge characterization is crucial for an efficient management of groundwater resources. In addition, recent droughts with unusually long periods of





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below average rainfall in Galicia have highlighted the vulnerability of groundwater resources to variations in recharge and have emphasized the need for reliable estimates of groundwater recharge. The first attempt of a global estimation of groundwater resources in Galicia (Xunta de Galicia, 1991) established a criterion based on theoretical infiltration indexes for different terrains. The total renewable resources were estimated in 2000 $Hm^3 yr^{-1}$ for all Galicia. By means of the hydrological model SIMPA, (Estrela et al., 1999) elevated this estimation to 2234 $Hm^3 yr^{-1}$ for only Galicia-Costa, which represents an average groundwater recharge of 18 % of precipitation. The last study about this topic (Xunta de Galicia, 2011) highlighted the large uncertainty in quantify the recharge in all Galicia-Costa due to the high heterogeneity of the terrain, and estimated the renewable resources by three different methodologies into a range of 3023–3689 $Hm^3 yr^{-1}$.

Groundwater recharge to shallow unconfined aquifers is complex and is dependent upon the occurrence, intensity, and duration of precipitation, temperature, humidity, wind velocity, as well as the characteristics and thickness of soil and rock above the water table, and the surface topography, vegetation, and land use (Memon, 1995). Groundwater recharge shows significant spatial and temporal variability as a consequence of variations in climatic conditions, land use, irrigation and hydrogeological heterogeneity (Sharma, 1989). The heterogenic hydrogeological characteristics of Galicia-Costa (mainly due to the variable fracturing degree of the bedrock) require a different approach for recharge quantification and a more comprehensive study for taking account of this variability.

Groundwater recharge can be quantified by different methods addressed at different hydrological zones to evaluate different timing of recharge, from potential values in the soil to some-delayed and smoothed net estimates in the saturated zone. Some approaches for recharge calculation are: water-table fluctuation method, seepage meters, lysimeters, isotopes, chloride mass balance (CMB) or modeling approaches. Each technique has advantages and disadvantages, and choosing the appropriate method for a particular site and study is often difficult. Selection must be taken based in different





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considerations: space/time scales factors, range, and reliability of recharge estimates based on different techniques (Scanlon et al., 2002). Uncertainties in each approach to estimating recharge underscore the need for application of multiple techniques to increase reliability of recharge estimates (Scanlon et al., 2002). Ideally, as many different approaches as possible should be used to estimate recharge.

In this study, two independent methodologies were applied. Firstly, a hydrological model based on water-table fluctuations and water-budget calculations using both surface-water and groundwater inputs, was used to estimate groundwater recharge to shallow aquifers. This hydrological model was applied to 9 small-size watersheds (ranging 0.23–26.26 $km^2$) in Galicia-Costa that are representative of the main geologies and climates existing in the District. Subsequently, a tracer technique (CMB) was used in order to cross-validate the results obtained by the principal methodology. The results obtained for the pilot catchments were finally extrapolated to the whole District by means of a GIS tool for the groundwater assessment of Galicia-Costa. Extrapolation was carried out according to geological and climatic criteria.

Both water balance models and CMB are proper methods for a watershed or regional approach (Flint et al., 2002). While CMB presents the advantage of a simple concept and few parameters needed, it has several limitations as assumptions not completely valid for fractured rocks or the high variability of Cl deposition rate with time, that increase the uncertainties in their results and for this reason they are used only for compare with model results. In contrast, limitations of water balance models, as equivalence of shallow infiltration and recharge (Flint et al., 2002), can be easily assumed for shallow aquifers present on fractured bedrock, while strengths as spatial and temporal distributions of recharge are desirable capabilities of modeling approach. Furthermore, where land uses and soil types are relatively uniform and limited data determines the choice of model, simple models provide a reasonable basis for long-term recharge estimates at the catchment scale compared to complex distributed models (Bradford et al., 2002).





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There are two major objectives of this study: firstly the quantification by two different techniques of groundwater recharge in the two main geologies present in Galicia-Costa (granites and metasedimentary rocks), its comparison and the sensitivity and uncertainty analysis of the estimates; secondly the global assessment of groundwater resources in Galicia-Costa by means of parameterization of recharge and its GIS-supported extrapolation and the analysis of the spatial and temporal variability of the resource.

## 2 Description of the study area

The Hydrologic District of Galicia-Costa is located on the North West coast of Spain (Fig. 1). It covers all the watersheds completely located inside the Autonomous Region of Galicia and extends over 13 072 km$^2$, where more than 2 000 000 people are settled. This means 44 % of the Galician territory and 75 % of its population. Due to the existence of many small aquifers developed on fractured and weathered bedrock, a different point of view was required for the study and characterization of the Galician hydrogeology. Accordingly, the whole territory was considered as a continuous groundwater body that must be protected. For a management reason, the Galician Water Administration (Augas de Galicia) defined 18 Groundwater Bodies following a geographic and topographic criteria instead a geologic criteria. The boundaries of each Groundwater Body coincide with the linked river watershed (Xunta de Galicia, 2003).

The main sources of the high recharge heterogeneity existing in Galicia-Costa are the different geology, the bedrock fracturing degree and the hydroclimatological conditions.

From a geological standpoint, Galicia-Costa can be divided in two main blocks (IGME, 2004): granitic rocks occupy around 38 % of the area, and metamorphic rocks (mainly slates, schist and gneisses) occupy 54 % of the total area. Both groups of rocks have been traditionally considered impervious or with very low permeability. However, they are frequently very fractured and weathered, and this secondary porosity can allow the storage of a considerable volume of water. As shown in the Fig. 1, the bedrock presents a vast net of faults and fractures. Some areas are specially fractured, like the northern quartzites, while other rock units are basically fresh, like the Ordes Complex in central Galicia.

There is also a high gradient of temperatures, evapotranspiration and precipitation (900–2500 mm $yr^{-1}$) from the coast line to the mountainous inland in Galicia-Costa (Galician Dorsal). Because the Galician aquifers are highly rain-recharge dependent and the residence time of the water in these aquifers is very short, climate conditions are relevant in the determination of the amount of recharge.

Land cover in Galicia-Costa is characterized by forest and grasslands mixed mosaics, with scattered small cultivation plots. Agriculture is mainly rainfed, so effects of irrigation on recharge can be neglected.

In order to characterize the aquifers in Galicia-Costa, nine lumped hydrological models were performed in small-size basins (0.23–26.26 $km^2$). The different lumped models cover granitic, quartzite and metasedimentary rocks, in coastal areas and inland areas, thus the different recharge rates in each condition can be analyzed.

## 3 Hydrological model

Visual Balan v2.0 (Samper et al., 2005) is a is a physically based water balance model for the simultaneous modeling of daily water balances in edaphic soil, in the unsaturated zone and in the aquifer, which takes into account the main processes of water flow in underground media. Parameter optimization is conducted by calibrating against multiple targets, such as groundwater levels and stream flow rates. This consideration of both surface water and groundwater as input data provides a framework that can be used to check continuity and better constrain model parameters and provides more reliable results than obtained only from surface-water data.

Visual Balan is a lumped model and provides a single recharge estimate for the entire catchment, thus it can only be applied to small catchments and requires a further upscaling for covering the entire Hydrologic District. On the other hand, small-scale applications allow more precise methods to be used to measure or estimate individual parameters of the water-budget equation (Healy et al., 1989).

Visual Balan has proven reliable and robust when reproducing measured values of prolonged monitoring tasks carried out in several catchments of NW Spain (Martínez et al., 2006; Raposo et al., 2010; Samper et al., 1997, 1999; Sena and Molinero, 2009; Soriano and Samper, 2000) and for recharge evaluation in other regions of Spain and Latin America (Candela et al., 2009; Carrica, 2004; Castañeda and García-Vera, 2008; Espinha-Marques et al., 2011; Garcia-Santos and Marzol, 2005; Jiménez-Martínez et al., 2010; Samper and Pisani, 2009; Weinzettel et al., 2002).

This model presents the advantages of using data that can be easily measured or estimated with reasonable accuracy (Jiménez-Martínez et al., 2010). Unknown parameters are calibrated by comparing computed stream flows and piezometric heads to measured data. The main input variables are daily temperature, precipitation, wind velocity, sunny hours, relative humidity, and soil-aquifer parameters (soil depth, porosity, field capacity, wilting point, hydraulic conductivity, and recession and storage coefficients).

According to Samper et al. (2005), three different regions can be distinguished in underground media, namely: (1) edaphic soil, in which flow is mainly vertical: infiltration of rainfall and irrigation water; evaporation and transpiration processes, etc.; (2) unsaturated zone, where vertical (percolation) and horizontal flows (interflow) coexist; and (3) the aquifer, or saturated zone, which may have discharge flows such as springs and streams. The water table oscillation is simulated in Visual Balan by means of the aquifer storage coefficient in responds to water inputs and outputs from the aquifer, regulated by different recharge and discharge coefficients. The stream flow is calculated as the sum surface runoff, interflow and groundwater discharge. Figure 2 shows the conceptual model for water flow between these three components. All the equations





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used by the model for the calculation of the water balance are described in detail by Samper et al. (2005) in the program manual, Castañeda and García-Vera (2008) and Jiménez-Martínez et al. (2010).

## 4 Chloride Mass Balance (CMB)

The climatic component in the groundwater chemical composition (Custodio, 1997; Murphy et al., 1996) is a function of the average chemical composition of precipitation. An accurate knowledge of this component allows explaining the presence of some ions in the groundwater and also estimating the average groundwater recharge by means of the mass balance of chemical components with a rainfall origin (Allison and Hughes, 1983; Rosenthal, 1987).

Chloride ion ($Cl^-$) is ideal to perform chemical balances because it remains inert during the recharge process (there is no significant long-term exchange with the environment) and, unlike water, it remains in the soil after evapotranspiration processes, it is highly soluble and usually has a known marine origin. This technique was widely used, both in the vadose zone and in the saturated-zone (Cook and Böhlke, 2000; Eriksson and Khunakasem, 1969; Sami and Hughes, 1996; Wood and Sanford, 1995). This study uses the CMB approach to evaluate the direct rainfall recharge, using sampling from the saturated-zone. The CMB approach spatially integrates recharge over areas upgradient from the measurement point. However, there remain problems of extrapolating point-source data to determine spatial variability of recharge. For that reason the specific results obtained by this technique will be mainly used for comparing with the hydrological model results.

The mass of $Cl^-$ deposition into the system is the sum of wet deposition dissolved with precipitation and dry fallout. If surface runoff is assumed to be zero, the total deposition (precipitation per the $Cl^-$ concentration in precipitation plus dry fallout) is equal to the mass out of the system (groundwater recharge per the $Cl^-$ concentration in the aquifer):





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$$P \times C_p = R \times C_{aq} + I \times C_i \tag{1}$$

where $R$ is average net recharge ($mm\,yr^{-1}$); $P$ is average annual precipitation ($mm\,yr^{-1}$); $I$ is average runoff (overland and interflow); $C_p$ is the effective average $Cl^-$ concentration in precipitation ($mg\,l^{-1}$), including the contribution from dry fallout; $C_{aq}$ is the measured Cl concentration in groundwater ($mg\,l^{-1}$); and $C_i$ is the average $Cl^-$ concentration in runoff and interflow ($mg\,l^{-1}$).

A zero surface runoff assumption is usually made for arid and semiarid climates. Although substantial surface runoff does not occur often in Galicia due to the high permeability of sandy soils, runoff can concentrate in washes or flows laterally along the soil/bedrock interface at the base of side slopes as interflow, which cannot be neglected. In humid climates, the overestimation of recharge due to ignore of chloride contribution by runoff and interflow may reach 50 % of the estimation (Alcalá and Custodio, 2008b).

Due to the lack of Chloride concentration data in runoff, a concentration factor ($F_c$) for calculating the Chloride concentration in runoff from Chloride concentration in rainfall can be used. According Prych (1998), in humid climates $F_c$ is only slightly above 1. In North Spain, (González-Arias et al., 2000) calculates a $F_c$ between 1 and 2, while Alcalá (2005) restricts its range between 1 and 1.5 and provides only one $F_c$ data for Galicia-Costa equal to 1.17. Assuming a homogenous concentration factor for the entire Galicia-Costa, groundwater recharge can be calculated as follow:

$$R = (P - I \times F_c) \times \frac{C_p}{C_{aq}} \tag{2}$$

The method appears to be valid for a first approximation of recharge in Galicia-Costa, as judged by its consistency with most other data sets discussed in this paper.

## 5 Data compilation and model setup

Model calibration was based on water monitoring data obtained at discharge gauges stations and wells within the study area. For each study catchment at least one well or gauge station at the watershed outlet is present (Fig. 3). Where both water data are available a more accurate calibration can be carried out. Water table data were measured in wells in a weekly basis. The most practical and used method of measuring the discharge of a stream is through the velocity-area method (World Meteorological Organization, 1980). Stream water velocity was measured in a weekly basis using a mini current meter. A stage-discharge relationship was developed for each gauge station. Most of the streams were monitored with automatic water-level pressure sensors that collect data in a 10-min basis in order to calculate continuous stream discharge. Daily average stream discharges were finally aggregated from 10-min data.

Climate data required by the models are daily precipitation, medium air temperature, daily sunny hours, relative humidity, wind speed and relationship between diurnal and nocturnal wind. For this study, all the historical climate inputs were obtained from 8 weather stations located in or close the studied catchments: Penedo do Galo, Muras, Fragavella, CIS-Ferrol, Pereiro, Mouriscade, Monte Castrove and Lourizan. The meteorological input data were obtained from Meteogalicia (Galician Meteorological Service), except the Muras weather station belonging to the University of Santiago de Compostela and placed specifically for this study. Missing data in the historical records were filled by correlations from nearest complete weather stations using statistical regressions. Average precipitation map in Galicia-Costa (Fig. 3) was built with data from Hydrological Plan of Galicia Costa using 151 pluviometric stations (Xunta de Galicia, 2003).

An initial value of model parameters was obtained by either field measurements (soil depth), bibliography (hydraulic conductivity) (López et al., 1998; Paz González et al., 2003, 2001) or values used for other similar close basins (recession and storage coefficients) (Samper et al., 1997, 1999; Soriano and Samper, 2000).





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Potential evapotranspiration can be calculated by the hydrological model by means of Thornthwhite, Blanney-Criddle, Makkink, Penman-Monteith or Turc methods. The Penman-Monteith method was chosen. Actual evapotranspiration was calculated by a modification of Penman-Gridley method (Samper et al., 2005). Superficial runoff was calculated using the curve number method. Finally, the Horton method (Horton, 1919) was used for the calculation of canopy interception.

## 6 Model calibration and results

Visual Balan includes an automated calibration procedure based on the Powell's method of multidimensional minimization (Press et al., 1989).

The calibration process consists in an initial autocalibration of the most sensible parameters taking as a starting point the initial range of values recommended by bibliography or used in similar basins. Finally, a more accurate manual calibration based on the knowledge of the basins hydrogeology was performed.

There is a positive gradient between precipitation and altitude in the Southwest coast of Galicia due to a rise of precipitation induced by orographic lift, while a rain shadow effect is observed from the coastal mountain range to inland areas (Carballeira et al., 1983). Due to this Foehn effect, Pereiro weather station collects a lower precipitation with respect the Umia catchment, and therefore measured rainfall is not completely representative for the Umia model. A correction factor of 1.1 was applied for correcting gauged rainfall, according the observed precipitation gradient for this orientation (Fig. 3).

The main parameters changed during the calibration process were: soil depth, soil hydraulic conductivity, percolation, interflow and aquifer recession coefficients, Curve Number and the aquifer storage coefficient (Table 1).

Figure 4 shows the fit obtained for modeled versus measured flow rates and water table levels in two of the study catchments. The statistical criteria used to evaluate the hydrologic goodness of fit were the coefficient of determination ($R^2$) and the model



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efficiency or Nash-Sutcliffe coefficient ($E$) (Nash and Sutcliffe, 1970). Both coefficients are highly affected by the good matching records of high values. Errors in discharge measurement increase substantially during floods. For this reason a Relative Nash-Sutcliffe Efficiency Criteria ($E_{rel}$) was also used for a more sensitive assessment during low flow conditions (Krause et al., 2005), since the main goal of this study is evaluate the groundwater recharge responsible of the stream base flow. The coefficient of determination for observed versus predicted daily stream flow in the different studied basins ranges from 0.74 to 0.98. The model efficiency ranges from 0.70 to 0.82. A better fit is obtained during low flow rates, as show the Relative Nash-Sutcliffe index which ranges from 0.76 to 0.87 (Table 2).

The three main factors in the hydrologic landscape that control water flow are classified by Winter (2001) as climate, topography, and the geologic framework. Rainfall supplies the land surface with water, the soil allows the water to infiltrate to the water table, and the deeper geologic framework provides the permeability necessary for deeper flow. If the climatic and soil conditions allow recharge to reach the water table at a rate that is greater than the saturated zone can transmit the recharge away, then the permeability of the geologic framework controls the recharge rate. This situation results in the condition of a relatively shallow water table, because storage of water underground backs up to the point that excess infiltration is diverted overland. In regions of relatively humid climates or low topographic relief, the geologic framework controls the rate of recharge (Sanford, 2002). These are the conditions present in Galicia, with high average precipitation and thin soils with relatively high permeability, where groundwater recharge is usually limited by permeability and storage capacity of deep fractured bedrock. As result of these conditions, water balance is usually dominated by interflow that flows laterally along the soil/bedrock interface.

In fact, it is not possible to establish a good relationship between groundwater recharge and annual precipitation, with a percentage of recharge varying from 13.7 % to 38.6 % depending on the different catchments studied (Table 2). The same conclusion was reached in different studies carried out in similar aquifers in north Portugal,





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where the recharge expressed as percentage of total precipitation varies widely from 1 % to 44 % (Alencoão et al., 2000; Da Silva Lima and Oliveira da Silva, 2000; Marques da Costa, 2000; Martins Carbalho et al., 2000; Mendes Oliveira and Lobo Ferreira, 2000; Pereira, 2000). The addition of geological criteria, reflecting the significant influence of the geologic framework on groundwater recharge, is clearly necessary.

In this study, two main geological blocks with different hydrogeological behavior were considered in Galicia-Costa: (a) quartzite and granitic rocks; (b) metasedimentary rocks (slates, schists and gneisses). Although quartzite is a metamorphic rock, for this study it is considered more similar to granites in a hydrogeologic point of view, due to its weathering products and high bedrock fracturing degree, that favor greater water storage capacities. Opposite, Galician schist and slates usually have closed fractures at high depth (Samper, 2003) therefore the aquifer storage capacity is quickly filled with high precipitation.

If all available recharge estimations in Galicia and North Portugal are plotted distinguishing the hydrogeology framework (Fig. 5), a clear relationship is now observed ($R^2 > 0.9$). Groundwater recharge increases with precipitation according a logistic curve, but the recharge threshold and growing rate are clearly different. The small thickness of soil usually present on schists (except in the "Ordes" Complex) favors the groundwater recharge even for low rainfall, while in the same conditions the deeper soil that may form in granite terrains favors the evapotranspiration. Besides, an asymptotic limit due to the aquifer storage capacity is observed (Alencoão et al., 2000). This limit is higher in granitic and quartzitic aquifers than in metasedimentary aquifers due to the greater secondary permeability (by weathering and rock fracturing) observed in granites and quartzite versus slates, schists and gneisses. Therefore granite formations are more interesting for groundwater purposes in areas with high precipitation, while schist behave better under moderate rainfall conditions.

Based on the daily water balance model, temporal variability of groundwater recharge was obtained for the nine pilot basins. Distribution of groundwater recharge along the year is strongly dependent on rainfall and presents minor differences





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depending on the geologic framework, following a similar pattern than precipitations. 74 % of groundwater recharge concentrates along the six first months of the hydrologic year, while during the summer (July, August and September) only 6.7 % of total recharge occurs (Fig. 6).

The unequal temporal distribution of rainfall and groundwater recharge, in combination with the limited storage capacity of fractured bedrock aquifers (average storage coefficient equal to 0.0059) and the short residence time of groundwater in them (average recession coefficient equal to 0.066 $day^{-1}$ and average time of semi-depletion of groundwater discharge equal to 22.85 days) reduces the availability of the resource for its exploitation.

## 7 Chloride mass balance results

Strong spatial variability in chloride deposition in coastal areas is one difficulty encountered in appropriately applying the CMB method. Coastal distance appears to be the most significant factor controlling chloride deposition in the study area; it can reach 70 % of spatial variability in chloride deposition (Guan et al., 2010).

In order to compute the CMB, a comprehensive bibliographic research was carried out with historic data of chloride concentration in rainfall in Galicia (Alcalá and Custodio, 2008a, b; Fernández-Sanjurjo et al., 1997; García-Rodeja et al., 1998; Gómez Rey et al., 2002; Prada-Sanchez et al., 1993; Silva et al., 2007; Vázquez et al., 2003). During 2008, a year with average precipitation within the normal range for Galician climate, 122 rainfall samplings were collected and analyzed in 56 locations where no bibliographic data were available in order to uniformly cover the entire District of Galicia Costa (Fig. 7a). Samplings were taken preferably close the basins where any hydrological model was performed, in order to compare the results. The sampling procedure consisted in the direct gathering of rainwater in a portable collector during different salient rainfall events and immediate transportation of samples to the laboratory to avoid possible evaporation effects and subsequent chloride concentration analysis.

This procedure assumes that $Cl^-$ dry deposition is negligible due to the wet Galician climate and high frequency of rainfall events.

On the other hand, since 2007 groundwater chloride concentration is being analyzed in a bimonthly basis in 54 locations included in the groundwater quality network of Augas de Galicia (Fig. 7b). These chloride data were completed with groundwater samplings collected in a sole field campaign in 2006 and with bibliographic data (Alcalá, 2005; Rodríguez Blanco et al., 2003).

An interpolation by inverse distance weighted method of punctual chloride data in groundwater and rainfall was carried out using a GIS tool.

Groundwater chloride concentration follows a geographic and topographic pattern (Guan et al., 2010): maximum concentrations are found in coastal areas, while minimum concentrations are found in mountain areas inland (Fig. 7b).

Assuming for Chloride mass balance purpose an average runoff (overland plus interflow) equal to 44.57 % of total precipitation (Table 2) and a homogeneous concentration factor equal to 1.17 (Alcalá, 2005), groundwater recharge was computed according Eq. (2). Maximum groundwater recharge is reached in mountain areas (Xistral, Suido and Testeiro Mountains) where high rainfall and high recharge rates converge (Fig. 7c).

Wherever groundwater recharge was obtained by both methodologies, hydrological model and CMB, a comparison of results is carried out (Table 3). The consistency of results obtained with both independent methods confirms the validity of groundwater recharge computed (Fig. 8).

## 8 Global groundwater resource assessment in Galicia-Costa

Reasonable estimates of recharge over extended areas can be derived using readily obtained field data, without considering the complicating aspects of small-scale (local) variability (de Vries and Simmers, 2002). The combination of reliable local data and GIS technology offers promise for a better understanding and quantification of recharge over large areas (de Vries and Simmers, 2002).





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A GIS tool was used aiming at extrapolating the results obtained for the analyzed basins to the whole area of Galicia Costa. A geodatabase was built comprising the main geologic, geographic, meteorological and demographic data concerning the whole area of Hydrographic District of Galicia Costa. The District territory was divided in four main blocks as a function of simplified geology that is assumed will have a similar hydrogeological behavior (Fig. 9a). Based on the studies carried out with hydrological models in the pilot basins and cross-validated with CMB, an equation as a function of total precipitation was established for calculating the groundwater recharge for each one of the two main hydrogeological areas in Galicia-Costa: granites and quartzite (Eq. 3) and metasedimentary rocks (Eq. 4).

$$\text{Recharge} = 62.425 + \frac{822.215}{\left(1 + 11.44 \times e^{-0.0264 \times P + 47.98}\right)^{0.139}} \quad (3)$$

$$\text{Recharge} = 88.425 + \frac{505.162}{\left(1 + 3.59 \times e^{-0.00275 \times P - 0.1143}\right)^{5.336}} \quad (4)$$

These empirical equations were obtained by minimizing the quadratic error function and provide a good fit of the different calculated recharge rates available in Galicia-Costa and North Portugal versus precipitation (Fig. 5) and allow a parameterization of recharge based on few parameters depending on geology with a hydrogeological meaning (Eq. 5).

$$\text{Recharge}\ (\text{mm yr}^{-1}) = A + \frac{K - A}{\left(1 + Q \times e^{-B \times P - M}\right)^{V}} \quad (5)$$

where $K$ and $A$ represent the maximum and minimum asymptotic limits of recharge, $B$ represent the recharge growth rate, $P$ is the annual precipitation in mm yr$^{-1}$ and $Q$, $M$ and $V$ are constants dependent on the geology.

The schistose Complex of Ordes, together with the neighboring basic and ultrabasic rocks, presents particular hydrogeological characteristics inside the group of metasedimentary rocks. Schists from the Complex of Ordes are less rich in quartz and therefore more easily weathered than the rest of slates, phyllites and schists present in Galicia (Fernández and Macías Vázquez, 1985), consequently soils developed over the Complex of Ordes reach greater depths. These soils also present silt-loamy textures that make them susceptible to surface crusting processes which significantly reduce groundwater infiltration during heavy rains (Paz González et al., 2001). According the IGME (Hernández Urroz et al., 1981), the rocks that constitute the Complex of Ordes have a negligible primary permeability and secondary permeability is very low. This Complex corresponds with an area with the lower density of faults and fractures in Galicia-Costa (Fig. 1), which reduces the water storage capacity in the secondary porosity of the bedrock. For all those reasons groundwater recharge rate in the Complex of Ordes is assumed lower than the rest of metasedimentary rocks. An average recharge of 8.4 % of total precipitation, obtained from CMB, is assumed.

Finally, quaternary deposits represent a very low area in Galicia Costa and the recharge coefficient for these detrital deposits is assumed 22 % of total precipitation (Control y Geología S.A., 2005).

Figure 9b shows the spatial distribution of groundwater recharge in Galicia Costa, depending on climatic and geological factors. Comparison of this map with those obtained by CMB (8c) shows a consistency in the results. Results indicate that the water-balance method is a powerful tool to understand the main features of recharge processes, if short time steps are used and the spatial variability of components is taken into account (de Vries and Simmers, 2002).

The greater groundwater recharge rate occurs in granitic areas with high annual precipitation in SW Galicia (Fig. 9b). Total groundwater resources in Galicia Costa are significant. An annual groundwater recharge of 4427 $Hm^3$ was estimated for the whole District, an amount significantly higher than estimated in previous studies.

Due to the large temporal and spatial variability of groundwater recharge, the short residence time of groundwater, the limited storage capacity of Galician fractured bedrock aquifers and technical difficulties for its full pumping, groundwater resources are particularly suitable for water supply to small villages and scattered rural population.





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According to recent statistical surveys there are almost 800 000 people (40.2 % of total population) in Galicia Costa living in villages of less than 500 people. With an average per capita water demand of 139 l day$^{-1}$ in Galicia (INE, 2009), water consumption in rural areas reaches 40.5 Hm$^3$ yr$^{-1}$. This represents less than 1 % of total groundwater resources, as calculated in the present paper. Therefore, the likely environmental impact derived from this use could safely be deemed negligible. This approach appears to be more sustainable than surface water-based solutions both from an ecological and economical point of view.

## 9 Uncertainty and sensitivity analysis

Groundwater recharge estimation contains several potential sources of uncertainty related to methodological approach, parameters estimation or upscaling process.

Combining and comparison of methods allows for knowing the deviation of estimates provided by different techniques applied in the same hydrological zone (Flint et al., 2002). Differences between punctual estimates with both used methods are lower than 7.7 % (Table 4).

The uncertainties associated with the model parameters were evaluated by computing the relative sensitivity criteria AS/CP (Eq. 6) defined by Jiménez-Martínez et al. (2010),

$$\text{Relative\_sensitivity}: \frac{\text{AS}}{\text{CP}} = \frac{|C_\text{s} - C_\text{b}| \times 100/C_\text{b}}{|P_\text{s} - P_\text{b}| \times 100/P_\text{b}} \quad (6)$$

where CP is the relative change of a given variable or parameter and AS is the relative change in the output (recharge) value, $P_\text{s}$ and $P_\text{b}$ are variable values used for sensitivity and calibrated base runs, respectively, and $C_\text{s}$ and $C_\text{b}$ are output data (recharge) computed in sensitivity and calibrated base runs, respectively. The magnitude of the parameter perturbation (CP) was fixed from −50 % to +100 % with respect to the original data, when tolerable ranges allows it. Figure 10 shows the effect on estimated



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recharge of a series of simulations where each parameter was modified according a fixed perturbation while all other parameters remain at their baseline value. Only the eight most sensitive parameters are showed. The most sensitive parameters are interflow and percolation recession coefficients, curve number and field capacity. The sensitivity criteria AS/CP is lower than 0.35 for the remaining model parameters.

The main uncertainty source for recharge estimation by CMB is the lack of data for Chloride concentration in runoff water and the assumption of a unique concentration factor ($F_c$) for the whole Galicia-Costa. A sensitivity analysis of $F_c$ on recharge estimation was carried out changing $F_c$ in the range of values observed in North Spain from 1 to 1.5 (Alcalá, 2005). A high sensitivity was observed with average variation of recharge estimates from −16.67 % to 32.35 % with respect the baseline obtained with $F_c = 1.17$.

## 10 Conclusions

A relation among groundwater recharge and total precipitation according to a logistic curve was found for both the two main geologies in Galicia-Costa. These curves satisfactorily reproduce the recharge values estimated in several pilot basins along the study area during different hydrological years that includes a range of climatic conditions. Despite both are fractured crystalline rocks, notable differences are observed in hydrogeological behavior of granite and metasedimentary rocks. Groundwater recharge is greater in schists than in granites when precipitation is moderate. However, schists present a lower storage capacity that limits the recharge when annual precipitation is higher, while recharge in granites continues to rise at a higher growth rate. Therefore granite formations are more interesting for groundwater purposes in areas with high precipitation. It is remarkable that precipitation higher than 1800–2000 mm yr$^{-1}$ practically do not contribute to a recharge increase since it full the storage capacity in both rock types and excess water is forced to flow as runoff and interflow.





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Total groundwater resources in Galicia-Costa were estimated in 4427 $Hm^3 yr^{-1}$, significantly higher than in previous studies.

Main uncertainties in model recharge estimations are associated with the large number of used parameters. However, only few parameters, namely interflow and percolation recession coefficients, curve number and field capacity, present high sensitivity on recharge estimation. Since modeled discharge and water table levels strongly depend on these parameters too, an accurate calibration of the models on a daily basis is required for a correct estimation of these sensitive parameters.

Uncertainty in recharge estimation with CMB method is mainly related with the assumption of the $F_c$ value. Because the large fraction of the water balance corresponding to runoff (overland plus interflow), Chloride concentration measures in runoff water are necessary for an accurate recharge estimation. Therefore, current estimates with a fixed $F_c$ must be considered only as orientative values.

Groundwater recharge shows a strongly unequal spatial distribution along Galicia-Costa, depending on climatic and geologic factors. Maximum recharge is found in South-west mountain areas, where high annual precipitation and fractured granitic bedrock are present.

The large temporal variability of groundwater recharge, the short residence time of groundwater, the limited storage capacity and small size of Galician aquifers on fractured bedrock difficult the exploitation of the resource by great pumping centers. However, groundwater resources are particularly suitable for water supply to small villages and scattered rural population by means of multiple small pumping centers. 40 % of total population of Galicia-Costa can be supplied by groundwater using less than 1 % of total resources, with minimum environmental impact.

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**Table 1.** Main parameters changed during the calibration process of the hydrological model and UTM coordinates of watersheds outlets (Projected Coordinate System: WGS 1984 UTM, Zone 29N).

| Parameter | Gafos | Lérez | Abeleda | Ferrol IV | Ferrol V | Landro I | Landro II | Umia | Mouro |
|---|---|---|---|---|---|---|---|---|---|
| Soil depth (m) | 1.43 | 0.65 | 0.646 | 1.61 | 1.5 | 0.6 | 1.61 | 2.022 | 1.1 |
| Hydraulic conductivity ($mm\,h^{-1}$) | 7.20 | 18.18 | 6.84 | 4.41 | 6.84 | 10.01 | 9.49 | 5.06 | 3.54 |
| Percolation recession coeff. (1/day) | 0.2476 | 0.2887 | 0.071 | 0.0397 | 0.6931 | 0.5915 | 0.2456 | 0.6125 | 0.7461 |
| Interflow recession coeff. (1/day) | 0.4621 | 0.3151 | 0.271 | 0.287 | 0.6301 | 0.2175 | 0.5509 | 0.3587 | 0.5776 |
| Aquifer recession coeff. (1/day) | 0.0277 | 0.062 | 0.03843 | 0.07749 | 0.0866 | 0.0184 | 0.009 | 0.2376 | 0.04067 |
| Aquifer storage coefficient | – | – | 0.01302 | 0.002664 | 0.00276 | – | 0.0051 | – | – |
| Curve Number | 55 | 55 | 55.2 | 60.3 | 56 | 55 | 60 | 40 | 44.15 |
| UTMX | 529424 | 557706 | 572784 | 559523 | 554284 | 611800 | 612608 | 551998 | 525630 |
| UTMY | 4697051 | 4719160 | 4716860 | 4815354 | 4813489 | 4813896 | 4828403 | 4721740 | 4699058 |
| Basin area ($km^2$) | 26.26 | 6.23 | 9.88 | 2.18 | 0.32 | 3.20 | 0.47 | 6.88 | 3.67 |
| Dominant geology | Granites | Schist | Schist | Granites | Granites | Granites/ Quartzite | Granites | Granites | Gneisses/ Schist |





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**Table 2.** Results and evaluation of the hydrologic goodness of fit in the studied catchments.

| Basin (calibration criteria) | Gafos (discharge) | Lérez (discharge) | Abeleda (discharge/ water-table) | Ferrol IV (discharge/ water-table) | Ferrol V (water-table) | Landro I (discharge) | Landro II (water-table) | Umia (discharge) | Mouro (discharge) |
|---|---|---|---|---|---|---|---|---|---|
| Average precipitation (mm $yr^{-1}$) | 1488 | 1598 | 1183 | 1254 | 1250 | 2029 | 1022 | 1996 | 2089 |
| $ET_o$ (%$P$) | 22.5 % | 10.6 % | 21.1 % | 37.5 % | 31.5 % | 21.9 % | 31.3 % | 14.2 % | 17.8 % |
| Groundwater Recharge (%$P$) | 15.9 % | 32.1 % | 27.2 % | 15.0 % | 16.8 % | 40.9 % | 9.1 % | 42.1 % | 25.5 % |
| Run-off (%$P$) | 11.0 % | 9.3 % | 3.7 % | 6.8 % | 3.8 % | 11.6 % | 2.7 % | 0.02 % | 5.1 % |
| Interflow (%$P$) | 42.7 % | 41.6 % | 41.3 % | 31.6 % | 41.2 % | 19.2 % | 46.1 % | 38.5 % | 42.7 % |
| Rainfall interception (%$P$) | 7.9 % | 6.4 % | 6.7 % | 9.1 % | 6.8 % | 6.4 % | 10.8 % | 6.2 % | 8.9 % |
| Coeff. $R^2$ | 0.8010 | 0.7413 | 0.7646/ 0.7369 | 0.8215/ 0.8025 | 0.8916 | 0.7850 | 0.9863 | 0.8579 | 0.7611 |
| Nash-Sutcliffe | 0.7014 | 0.7138 | 0.7489 | 0.8174 | – | 0.7460 | – | 0.7961 | 0.8218 |
| Relative Nash-Sutcliffe | 0.8530 | 0.8370 | 0.8480 | 0.7745 | – | 0.8732 | – | 0.8566 | 0.8185 |





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**Table 3.** Comparison of groundwater recharge computed by different methodologies.

| Basin | $[Cl^-_{rainfall}]$ ($mg\,l^{-1}$) | $[Cl^-_{GW}]$ ($mg\,l^{-1}$) | Interflow + runoff (% precip.) | Recharge rate (% precipitation) | |
|---|---|---|---|---|---|
| | | | | Chloride mass balance | Hydrological model |
| Ferrol IV + V | 12.54 | 35 | 41.65 % | 18.37 % | 15.9 % |
| Landro I | 5.51 | 7.88 | 30.8 % | 44.77 % | 40.9 % |
| Lérez | 4.47 | 6.03 | 50.9 % | 29.98 % | 32.1 % |
| Gafos | 4.21 | 12.39 | 53.7 % | 12.63 % | 15.9 % |
| Umia | 4.47 | 7.05 | 38.5 % | 34.44 % | 42.1 % |
| Landro II | 7.57 | 20.71 | 48.8 % | 15.68 % | 9.1 % |
| Mouro | 6.01 | 13.31 | 47.8 % | 19.90 % | 25.5 % |
| Valiñas | 3.42 | 13.32 | 45.9 % * | 11.89 % | 8.8 % * |

* Model data from Samper et al. (1997).



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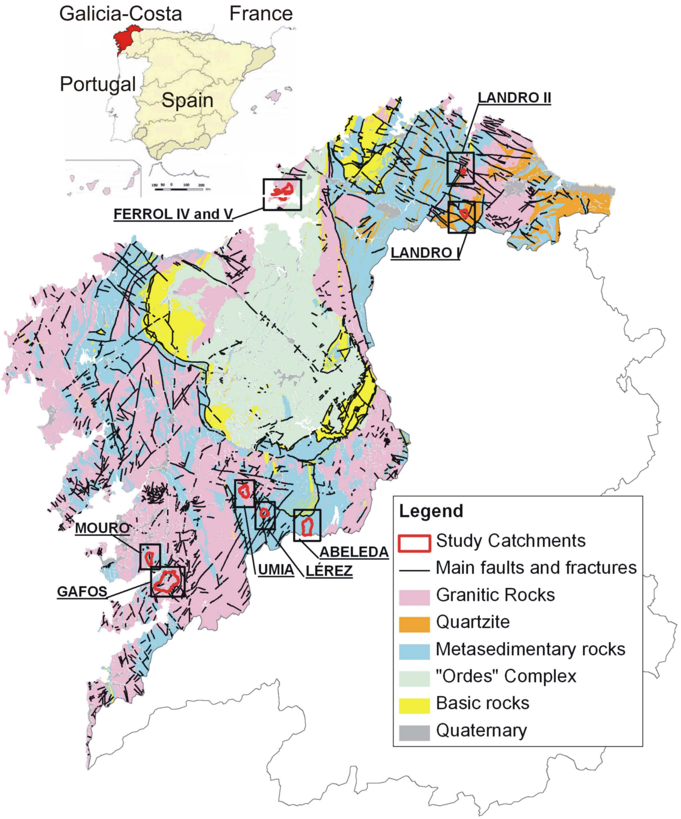


**Fig. 1.** Location of the Hydrologic District of Galicia-Costa in the Spanish hydraulic division, the study catchments and geological map [elaborated from GEODE geological map (IGME 2004)].





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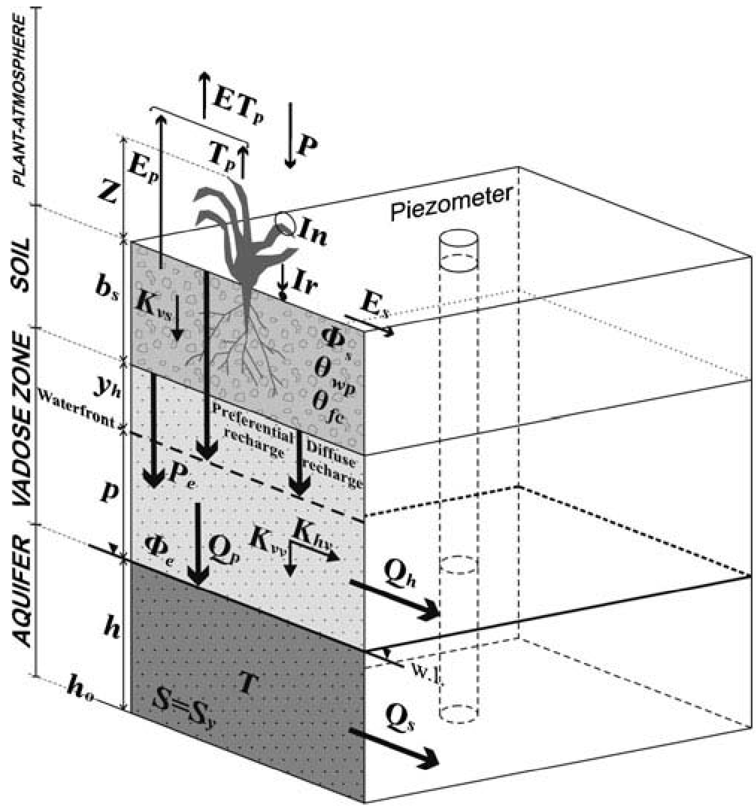


**Fig. 2.** Main components of water budget considered under the framework of the computer program Visual Balan (Samper et al., 2005; Jiménez-Martínez et al., 2010).

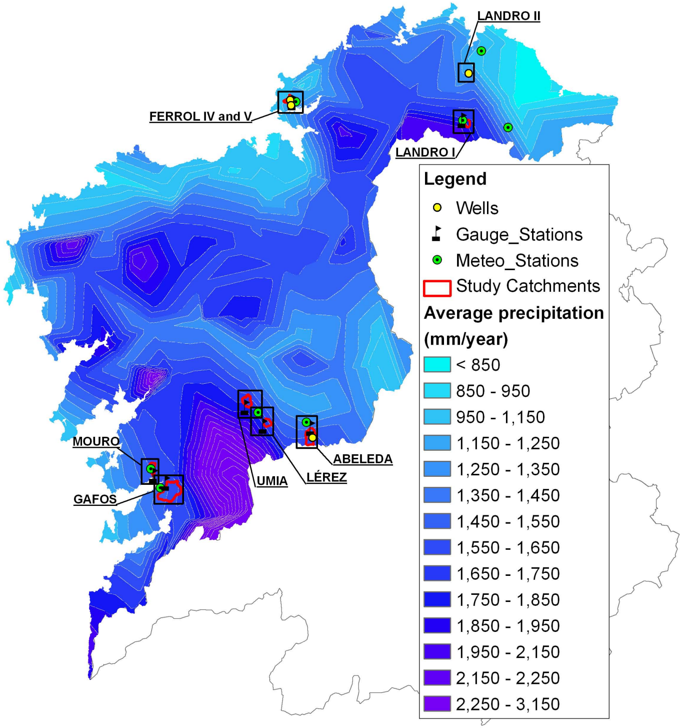


**Fig. 3.** Location of weather stations, wells and discharge gauge stations used for modeling the study catchments, and average precipitation map for Galicia-Costa built with data from Hydrological Plan of Galicia Costa (Xunta de Galicia, 2003).





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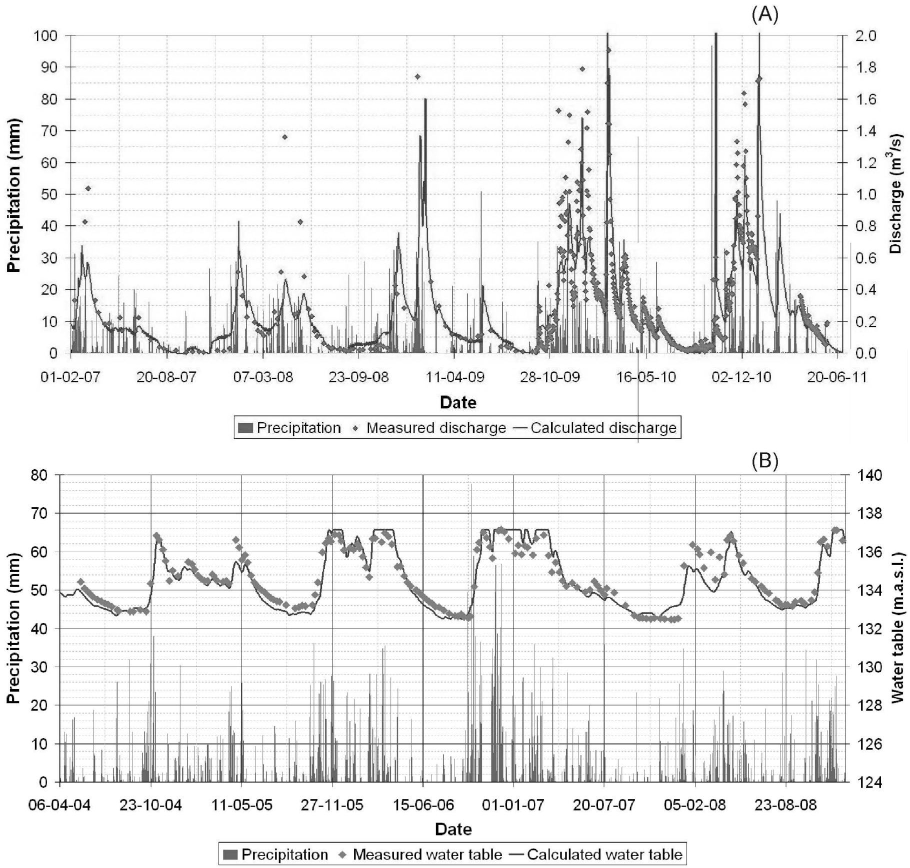


**Fig. 4.** Modeled versus measured flow rates in Abeleda Catchment **(A)** and modeled versus measured water table levels in Ferrol V Catchment **(B)**.





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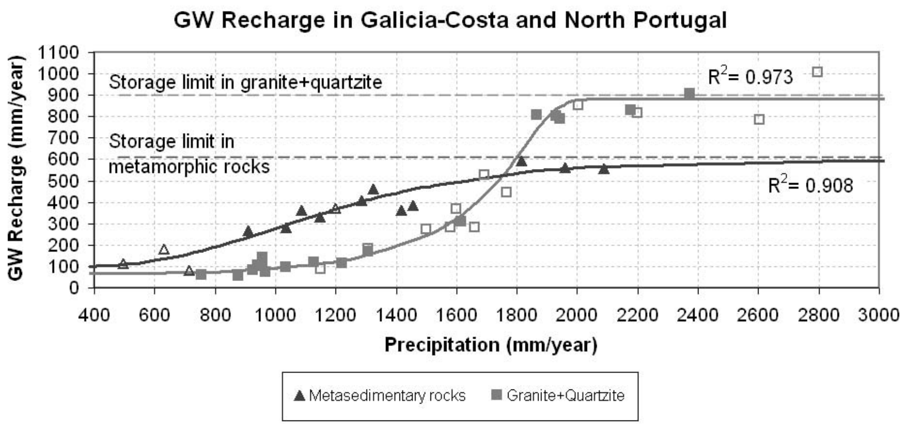


**Fig. 5.** Relationship between groundwater recharge and precipitation, depending on the geology. Filled symbols correspond with data gathered in Galicia Costa area; other data were gathered from catchments in the nearby Northern Portugal.





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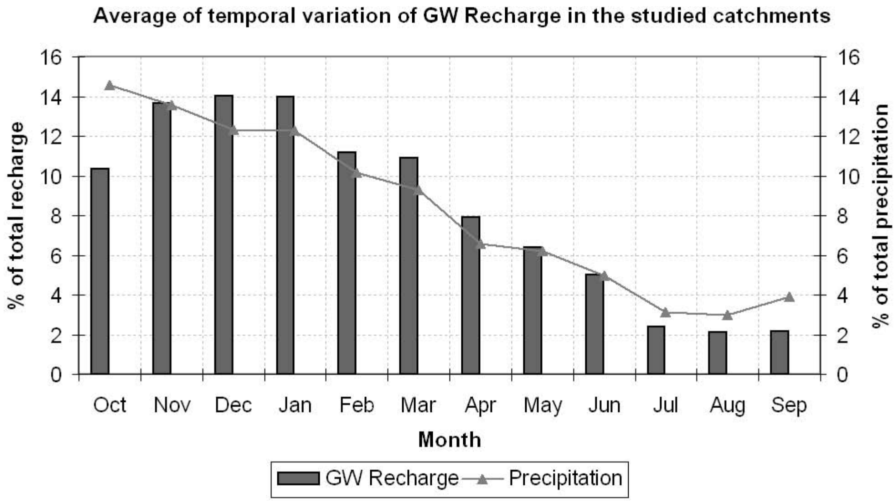


**Fig. 6.** Temporal variability of groundwater recharge: average percentage of monthly groundwater recharge and precipitation along the year in the nine pilot catchments.





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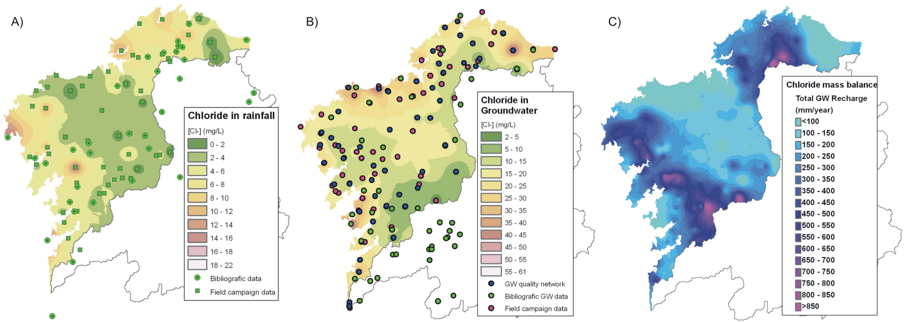


**Fig. 7.** Map of chloride concentration in rainfall **(A)**, in groundwater **(B)**, and groundwater recharge computed by chloride mass balance **(C)**.





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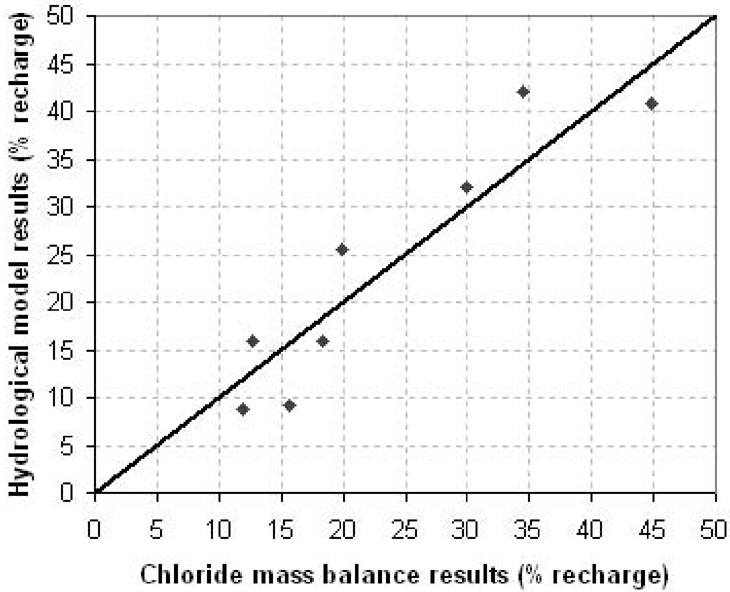


**Fig. 8.** Groundwater recharge computed by hydrological models versus chloride mass balance results.



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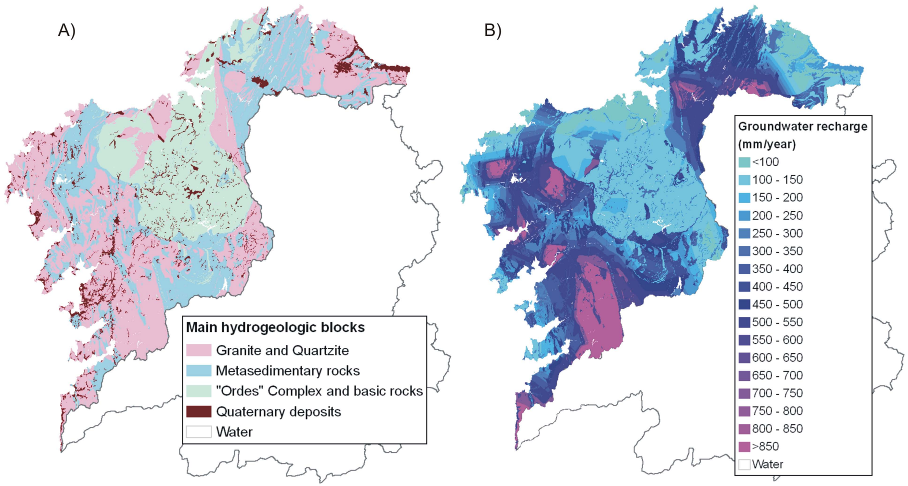


**Fig. 9.** Main geological units **(A)** considered for extrapolation of water balance models results and groundwater recharge **(B)** obtained for Galicia-Costa District by a GIS tool as a function of precipitation and geology.





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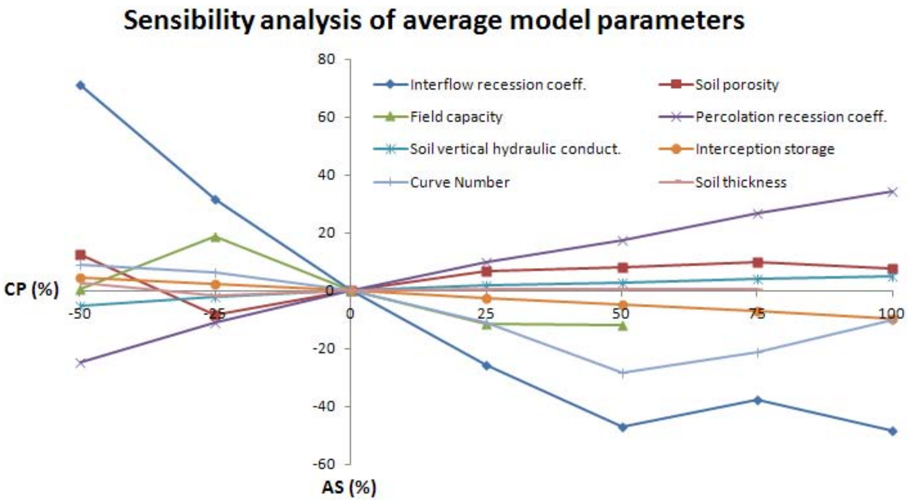


**Fig. 10.** Sensitivity analysis of model parameters on estimated recharge, average results for the nine pilot basins (only the eight most sensitive parameters are showed).





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