Assessing the impact of future climate change on groundwater recharge in Galicia-Costa, Spain

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Abstract Climate change can impact the hydrological processes of a watershed and may result in problems with future water supply for large sections of the population. Results from the FP5 PRUDENCE project suggest significant changes in temperature and precipitation over Europe. In this study, the Soil and Water Assessment Tool (SWAT) model was used to assess the potential impacts of climate change on groundwater recharge in the hydrological district of Galicia-Costa, Spain. Climate projections from two general circulation models and eight different regional climate models were used for the assessment and two climate-change scenarios were evaluated. Calibration and validation of the model were performed using a daily time-step in four representative catchments in the district. The effects on modeled mean annual groundwater recharge are small, partly due to the greater stomatal efficiency of plants in response to increased CO_2 concentration. However, climate change strongly influences the temporal variability of modeled groundwater recharge. Recharge may concentrate in the winter season and dramatically decrease in the summer–autumn season. As a result, the dry-season duration may be increased on average by almost 30% for the A2 emission scenario, exacerbating the current problems in water supply.

Keywords Climate change · Impact · Groundwater recharge · SWAT · Spain

Received: 5 March 2012 / Accepted: 19 October 2012

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Introduction

Fossil-fuel consumption has caused an increase in anthropogenic emissions of carbon dioxide (CO_2) and other greenhouse gases (IPCC 2007). Based on the range of emission scenarios presented to the Intergovernmental Panel on Climate Change (IPCC 2007), CO_2 concentrations are expected to increase from the present-day concentration of approximately 330 parts per million (ppm) to between approximately 550 and 970 ppm. Many general circulation model (GCM) experiments have been performed in the past two decades to investigate the effects of increasing greenhouse-gas concentrations. These studies predict a rise in global mean temperature over the period 1900 to 2100 of between 1.1 and 6.4 °C, depending on the different scenarios (IPCC 2007). Predicted changes in precipitation are more speculative than the temperature projections, especially for smaller regions, but modifications of rainfall patterns are expected, both in intensity and in total amount. Changes in the temporal and spatial distribution of precipitation can also increase the risk of both heavy rainfall events and droughts. A general consensus is that the average global surface temperature has risen by 0.45–0.6 °C during the last century (IPCC 2001; Marshall and Randhir 2008). These changes in temperature and precipitation could impact the hydrological cycle and various processes of a watershed system. Specific potential impacts at watershed scale include changes in run-off, nutrient enrichment, sediment loading, and evapotranspiration rates (Band et al. 1996; Chang et al. 2001; Evans et al. 2003). Groundwater in shallow aquifers is part of the hydrological cycle and is affected by climate variability and change through recharge processes (Chen et al. 2002). Consequently, climate change affects the availability of freshwater for both ecosystem and human uses (Carpenter et al. 1992; IPCC 2001).

In spite of the extensive research on climate change and the great number of new studies in climate-change downscaling that have been published in recent years, more restricted growth has been seen in publications that use downscaling methods to examine hydrological impacts (Fowler et al. 2007). Hendricks Franssen (2009) and Green et al. (2011) present extensive literature reviews of the potential impacts of climate change on groundwater, and summarize the findings from a number of case studies throughout the world. More recently, a

DOI 10.1007/s10040-012-0922-7

growing number of case studies have been carried out to assess the regional effects of climate change on groundwater (Crosbie et al. 2010; Essink et al. 2010; Jackson et al. 2011; Loaiciga 2009; Stoll et al. 2011; Okkonen 2011; Clilverd et al. 2011; Treidel et al. 2012; Neukum and Azzam 2012; Barthel et al. 2012; Ali et al. 2012; Scott et al. 2012).

Many climate-change studies have predicted reduced recharge (Serrat-Capdevila et al. 2007; Wegehenkel and Kersebaum 2009; Ali et al. 2012) and decrease in groundwater levels (Hsu et al. 2007; Barthel et al. 2012; Goderniaux et al. 2009); however, the effects of climate change on recharge may not necessarily be negative in all aquifers during all periods of time (Green et al. 2011). Stoll et al. (2011) did not predict future groundwater stress in a catchment in northern Switzerland. Furthermore, studies in northern cold regions predict increasing groundwater recharge in the future due to reduced extent of ground frost (Jyrkama and Sykes 2007; Kovalevskii 2007; Clilverd et al. 2011; Okkonen 2011). Moreover, when multiple future climate scenarios are used, even the prediction of the direction of the change in recharge may be difficult and vary over a wide range from increases to decreases, depending on each climate model and scenario (Crosbie et al. 2010; Allen et al. 2010).

Most studies investigating the impact of climate change on groundwater resources in Europe predict decreasing groundwater recharge and declining water tables (Bates et al. 2008; Stoll et al. 2011). Additionally, a greater seasonal variation in the groundwater resource is predicted, with higher recharge rates during a reduced period of time in winter and spring and less groundwater recharge during summer and autumn (Herrera-Pantoja and Hiscock 2008; Jackson el al. 2011; Neukum and Azzam 2012).

Relatively few studies have examined the effects of climate change on groundwater resources in Spain, and they are focused on the Mediterranean and southern regions with drier climate (Manzano et al. 1998; Younger et al. 2002; Custodio et al. 2007; Samper et al. 2007; Samper et al. 2009a; Aguilera and Murillo 2009; Candela et al. 2009; Guardiola-Albert and Jackson 2011; Hiscock et al. 2012). All these studies are consistent in predicting a reduction in groundwater recharge. Additionally, a significant intra-annual variability of recharge is predicted, with a reduction of groundwater recharge throughout the initial autumn period (Candela et al. 2009).

Hydrological models can be used to link climate-change studies and hydrological impact assessments. Hydrological models can be combined with climate scenarios generated from downscaling of GCMs to produce potential scenarios of climate-change effects on water resources at a watershed scale. These hydrological models provide a link between climate change and water yields through simulation of hydrological processes within watersheds (Ficklin et al. 2009).

In the European context, under Framework Programme 5, the PRUDENCE project (Christensen et al. 2007) has provided a set of experiments using ensemble runs, different regional climate models (RCMs), different driving GCMs and different emissions scenarios for the European region. The data provided by this project have so far been little used for impact assessments. The Spanish Meteorological Agency (AEMet) has elaborated the regional projection of climate change for Spain (AEMet 2009) based on the data from the PRUDENCE project.

The choice of driving GCM generally provides the largest source of uncertainty in downscaled scenarios (Boé et al. 2007; Fowler et al. 2007). In addition, each step of the downscaling procedure also has associated uncertainty. All these uncertainties add up and constitute a cascade of uncertainty that affects the final result of a climate projection (Quintana Seguí et al. 2010). Leung et al. (2003) suggest that for developing credible high-resolution climate simulations for impact assessment, a logical approach is to use multiple GCMs and RCMs with multiple ensembles. In this way, the present study used the climate projections elaborated by the AEMet as inputs to the hydrological model SWAT (Arnold et al. 1998) for assessing the climate-change effects in the hydrological district of Galicia-Costa (in the northwest of Spain), focusing especially on the impacts on groundwater recharge. Two GCMs (HadAM3H and ECHAM4) and eight different RCMs were used as ensembles in order to assess the uncertainty due to the different models.

Hard-rock formations (composed of igneous and metamorphic rocks) cover more than 20 % of the land surface (Ayraud et al. 2008). Groundwater from fissured hard-rock aquifers constitutes an important water resource in many European regions (Raposo et al. 2012) and its use is increasing in response to the increasing demand for water and the degradation of surface river-water quality (Ayraud et al. 2008). However, fissured aquifers are highly vulnerable to variations in recharge, due to their low storativity, which may represent only 3 years of average infiltration (Wyns et al. 2004). Shallow hard-rock aquifers supply drinking water for many rural communities in Europe, but frequently, summer drought results in significant lowering of the water table and drying up of springs and wells (Stoll et al. 2011). In this context, fissured aquifers in Galicia-Costa are expected to be very sensitive to climate change, due to their low storage capacity and the short residence-time of the water, which make them highly dependent on rainfall-recharge (Raposo et al. 2012). A decrease in groundwater recharge and the consequent water table decline may affect the water supply for a quarter of the population of Galicia-Costa that depend on these groundwater resources (Romay and Gañete 2007). Green et al. (2007) demonstrated the potential importance of changes in the timing of rainfall on recharge. Groundwater recharge can disproportionately change with respect to rainfall. This result is related primarily to the increased frequency of long-duration wet and dry periods. Furthermore, apparent positive effects of climate change on annual net recharge can mask negative effects on a sub-annual time basis (Green et al. 2007). The changes in the timing of rainfall may strongly impact on these especially vulnerable shallow aquifers. Evaluation of climate change on a watershed system is important, in order to develop alternative strategies and policies to mitigate the impacts of global warming (IPCC 2001).

The main objective of this study is quantifying the impact of future climate change on groundwater recharge in Galicia-Costa. For that aim, the following specific objectives were posed: to characterize four different pilot watersheds in Galicia-Costa by means of calibration and validation of hydrological models using historical climate data and comparing simulated outputs with measured stream discharge rates in rivers; to estimate variations in seasonal and average annual groundwater recharge in response to different climate-change scenarios; and to assess the uncertainty due to the use of different GCMs, RCMs and different emissions scenarios.

This report begins with a description of the study area and the importance of groundwater in Galicia-Costa. The hydrological model and the data collection process are then described, followed by the model calibration and validation for the pilot watersheds. Finally, the incorporation of climate-change scenarios into the models is described, followed by a discussion of the main results.

Description of the study area

The hydrological district of Galicia-Costa is located on the northwest coast of Spain (Fig. 1). It contains all of the watersheds entirely located inside the autonomous region of Galicia, it extends over an area of 13,072 km^2 (44 % of the Galician territory), and is where more than 2,000,000 people are settled (75 % of the Galician population). Due to the existence of many small aquifers developed on fractured and weathered bedrock throughout the district, and the difficulty of individually characterizing each separate aquifer, an aggregate approach was required for the study of Galician hydrogeology. Accordingly, the whole territory was considered as a continuous groundwater body that must be protected. For management purposes, the Galician water administration (Augas de Galicia) defined 18 groundwater bodies following geographic and topographic criteria rather than geologic criteria. The boundaries of each groundwater body coincide with the linked river watershed (Xunta de Galicia 2003).

According the Köppen-Geiger climate classification (Kottek et al. 2006), almost the whole of Galicia has a warm temperate climate with dry and warm summers (Csb), characterized by maximum seasonal rainfall in winter and minimum in summer. The bordering Cantabrian area has a warm temperate climate, fully humid with warm summers (Cfb), which differs from Csb climate in having a more homogeneous distribution of precipitation through the year.

From a geological standpoint, Galicia-Costa can be divided in two main blocks: granitic rocks, which occupy around 38 % of the area; and metamorphic rocks (mainly slates, schist and gneisses), which occupy 54 % of the total area. Both groups of rocks have traditionally been considered to be impervious or to have very low permeability. However, they are frequently very fractured and weathered and possess a vast network of faults and fractures (Fig. 1), and this secondary porosity can allow the storage of a considerable volume of water. Specific storage and hydraulic conductivity values for the aquifers exhibit high variability, due to the heterogeneity of the fractured bedrock.

There is also a high gradient of temperature, evapotranspiration and precipitation from the coast of Galicia-Costa to the mountainous inland area (Galician Dorsal). For example, precipitation ranges from 900 mm/year at the coast to 2,500 mm/years in some points of Galician Dorsal. Because the Galician aquifers are highly dependent on rainfall-recharge, with relatively low specific storage and short residence times for groundwater, climatic conditions, like the rainfall regime, are especially relevant to the determination of the amount of recharge and availability of groundwater resources throughout the year.

From a land-use standpoint, most of the territory of Galicia-Costa is occupied by forests (mainly pine, eucalyptus and mixed forests), representing 35.6 % of the total area. Croplands cover 36.7 %, and rangelands (brush and grasses) cover 24.2 % of the area. Urban areas, wetlands and water bodies represent the remaining 3.5 % of the district. Regarding the soil classes present in Galicia-Costa, there are two main soils types according the FAO90 classification (FAO 1990): regosols (covering 57.6 % of the total area) and leptosols (covering 40.0 % of the total area). Minor soil types like histosols and podzols represent only 2.4 % of the total area.

In order to characterize the aquifers in Galicia-Costa, four semi-distributed SWAT models were constructed for four medium-sized basins (ranging in area from 102.2 to 544.7 km^2): two Cantabrian basins (Landro and Mera rivers), one Atlantic basin (Anllóns River) and one inland basin (Deza River). The total area of all studied basins is 1262.3 km^2, which represents 9.66 % of the entire hydrological district of Galicia-Costa (Fig. 2).

Groundwater uses in Galicia-Costa

The high quality and easy availability of groundwater in Galicia-Costa, and the shallow depth of the water table, have resulted in traditional use of these resources by the population, especially in rural areas. Groundwater has proved an optimal source for water supply in rural areas (Raposo et al. 2012). Due to the scattered distribution of the aquifers and the traditional settlement pattern in Galicia characterized by dispersion (about 40 % of the population lives in small rural villages with fewer than 500 inhabitants or in isolated houses), the water sources can be located close to the consumption center, reducing the difficulties of water transportation. This strategy was used by both private individuals and the public administration. According to the water supply plan of Galicia (Xunta de Galicia 2005), 75 % of the registered water sources use groundwater, although surface water represents the larger resource in terms of consumed volume. A quarter of the population in Galicia-Costa uses a private water supply (Romay and Gañete 2007), by means of

DOI 10.1007/s10040-012-0922-7

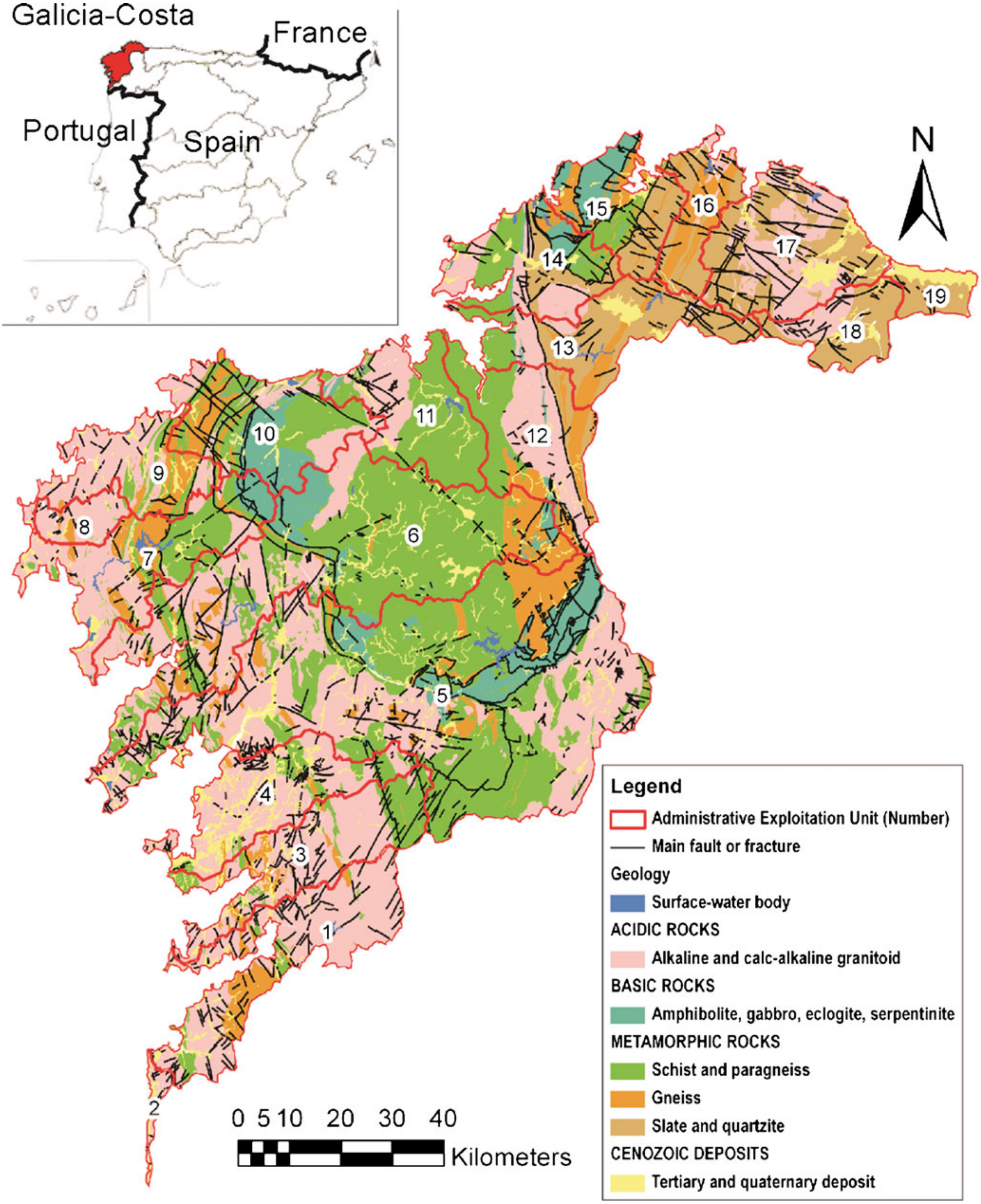

Fig. 1 Location of the hydrological district of Galicia-Costa within Spain (national boundaries in *thick line*) and within the Spanish hydraulic division (*fine line*), and geological map [elaborated from GEODE geological map (IGME 2004)]

individual or communal groundwater facilities, mainly natural springs or shallow dug wells that pump water from the shallow aquifer in the weathered rock. Due to their low storativity, limited specific yield and the expected

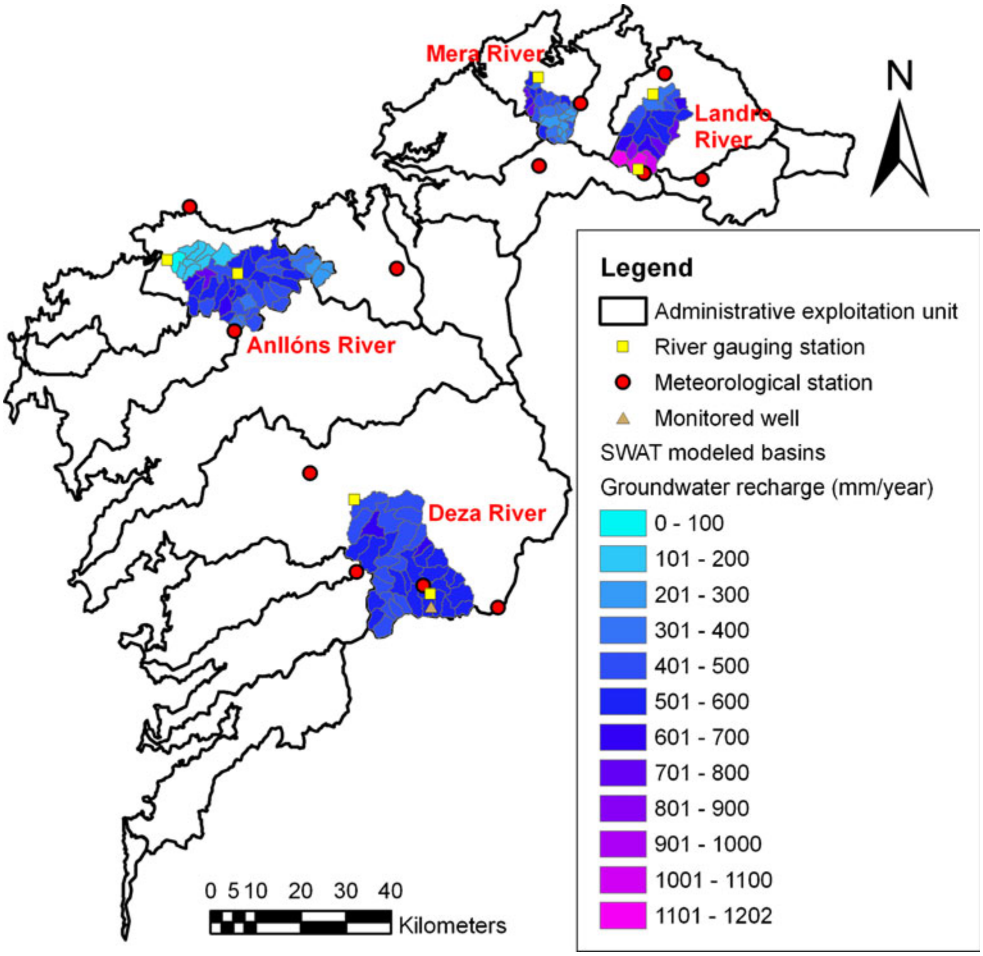

Fig. 2 Location of basins modeled with SWAT, showing their calculated groundwater recharge (by sub-basin)

short residence times of groundwater in the weathered zone (Raposo et al. 2012; Ayraud et al. 2008), these shallow aquifers are highly vulnerable to climate variability and very sensitive to long dry periods. The shallow depth of the dug wells in Galicia makes them very vulnerable to small drawdowns of the water table (Raposo et al. 2010), and it is common for wells and springs to rapidly diminish and dry up, following periods of several months with low precipitation. Predictions of climate change in Galicia show a decrease in the total volume of precipitation and a concentration of rainfall into fewer events through the year, mainly during the winter season (AEMet 2009), aggravating the already common dry periods in summer. A quarter of the population in Galicia-Costa could therefore be adversely affected by climate change. Accurate prediction and quantification of these impacts is necessary, in order to develop mitigation measures for guaranteeing the water supply to all the population.

Hydrological conceptual model

Due to their strong heterogeneity (in lithology, degree of fracturing, metamorphism, etc.), hard-rock aquifers are difficult to characterize. Thanks to recent works, weathering processes in this type of rock are now better understood (Lachassagne et al. 2001; Wyns et al. 2004; Dewandel et al. 2006; Ayraud et al. 2008), and a conceptual model originally developed for granitic bedrock has proved to be applicable to all types of hard-rock aquifers (Durand et al. 2006). It has been established that in crystalline basement rocks, weathering profiles are characterized by regional stratiform zones that are parallel to the paleo-weathering surfaces (Wyns et al. 2004), resulting in three main aquifer layers: an unconsolidated saprolite (or regolith), and an upper and a lower fissured zone. The bottom of the aquifer is defined by the fresh basement (Fig. 3).

The cover of unconsolidated saprolite, several meters thick, can reach quite a high porosity because of its clayey-sandy composition, which depends on the lithology of the parent rock. Saprolite can be considered as a porous medium, and where this layer is saturated, it provides the majority of the groundwater storage in this type of composite aquifer (Dewandel et al. 2006) and used to be exploited by most of the traditional shallow wells dug in this area.

Beneath this layer, a fissured zone, generally some 50 m thick, is characterized by low porosity. In a fissured

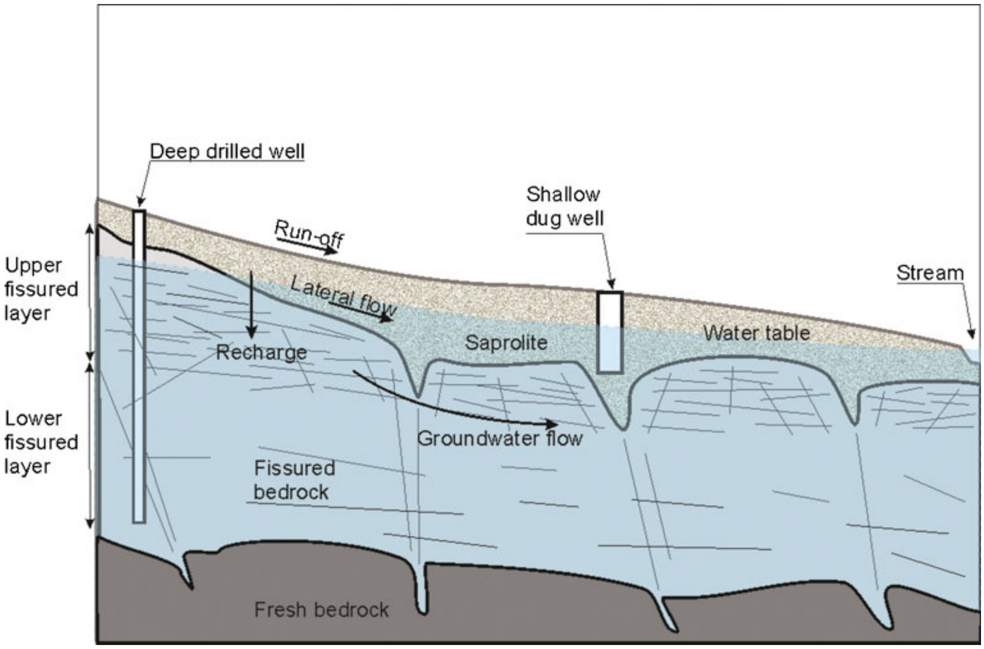

Fig. 3 Hydrological conceptual model for Galician fissured aquifers in crystalline rock (*the blue colour* represents the saturated zone)

medium, the aquifer properties will depend on fissure and fracture connection and distribution. The fissured layer is generally characterized by a dense horizontal fissuring in the first few metres, with the density of fissures decreasing as depth increases. The concentration of this horizontal fissuring at the top of the fissured layer constitutes the upper fissured zone. This zone accounts for most of the transmissivity in the composite aquifer, and is exploited by most of the deep wells drilled in hard-rock areas. However, where the covering saprolite layer is very thin or unsaturated, the fissured layer also provides the storage function of the composite aquifer (Dewandel et al. 2006).

Finally, the fresh basement is permeable only locally, where tectonic fractures are present. The fracture density with depth is much lower than within the fissured layer. At catchment scale, and for water resources applications, the fresh basement can then be considered as impermeable and of very low storativity (Maréchal et al. 2004).

In accordance with this general conceptual model, the hydrogeological data obtained from different sites in Galicia-Costa indicate the existence of two subsurface flow systems (Soriano and Samper 2003). A shallow aquifer, generally less than 20 m thick, developed within the rock-weathering zone. Underlying this aquifer, a less permeable aquitard is found in the fractured rock, where water flows mostly through fractures (Soriano and Samper 2003). The thickness of the fractured-rock zone varies significantly from site to site depending on the tectonic history of the bedrock, within a range of 30–100 m (Raposo et al. 2012). In the shallow aquifer, the phreatic surface reproduces in a smooth manner the shape of the topographic surface, and groundwater and surface-water catchment boundaries are assumed to be coincident. The water table is only a few meters below the surface and shows fast-rising and smooth-falling patterns in response to wet and dry periods (Samper 2003), with annual level oscillations from 1.5 to 4 m (Soriano and Samper 2003). In winter, the water table usually rises to a level that marks a maximum recharge level (the rooted zone in the soil) (Soriano and Samper 2000). A major hydrogeological division exists between the weathered layer and the fissured-fractured layer (Ayraud et al. 2008). The contrast in proprieties between these two layers favors lateral flows along the saprolite/rock interface, which represent an important component of the water balance (Raposo et al. 2012).

Assessing precise characteristics of this type of aquifer and determining hydrogeologically equivalent properties at different scales is difficult (Ayraud et al. 2008). Due to their apparent heterogeneity, discontinuity and anisotropy, the hydrodynamics in the fissured layer have not been described in detail; yields, permeabilities or specific capacities are the main information available for these composite aquifers. Specific storage calculated by pumping tests or estimated by models varies widely, from 0.00032 in deep boreholes to 0.013 in shallow dug wells (Soriano and Samper 2000; Franco Bastianelli 2010; Raposo et al. 2012). Similarly, transmissivity varies from 0.5 to 15 m^2/day (Soriano and Samper 2003). Finally, typical yields of wells usually vary from 0.3 to 5.0 L/s, but exceptionally can reach 40 L/s (Samper 2003; Xunta de Galicia 1991).

Modeling methodology

For this study, the watershed system was simulated with the Soil Water Assessment Tool (SWAT) model (Arnold et al. 1998). SWAT is a physically based long-term continuous time and watershed-scale model developed initially to predict the impact of agricultural or land management practices on water, sediment and agricultural chemical yields in large complex watersheds. However, it is also capable of predicting water yield, nutrient, and sediment loading under climate-change scenarios (Neitsch et al. 2002). SWAT is a semi-distributed model operating on a daily time-step. A high level of spatial variability can be simulated, since SWAT allows the division of the watershed into a large number of subwatersheds, which are then further subdivided into unique soil/land-use/slope characteristic areas called hydrological response units (HRUs). The HRUs are defined by means of a coupled-GIS (geographical information system) tool and for this purpose, a digital-elevation model, land cover and soil maps are needed. The water balance is the main driving force in SWAT and it is calculated for each HRU. Flow generation and sediment yield are later summed across all HRUs in each subwatershed, and the resulting loads are then routed through the river channels, ponds or reservoirs to the watershed outlet. An HRU water balance is represented by five storage components: canopy interception, snow, soil profile, shallow aquifer, and deep aquifer.

SWAT allows a number of different physical processes to be simulated in a watershed: climate, hydrology, plant growth, erosion, nutrient transport and transformation, pesticide transport, and management practices. The hydrology part of the model includes snowmelt, surface runoff, evapotranspiration, groundwater percolation, lateral flow, and return flow to the river. More detailed descriptions of the different model components can be found in Arnold et al. (1998) and Neitsch et al. (2002).

SWAT has gained international acceptance as a robust interdisciplinary watershed-modeling tool (Gassman et al. 2007). It has been used in many international applications and has proven reliable for fitting flow-rate data, measured and modeled, for a variety of watershed scales (e.g., Rosenthal et al. 1995; Arnold and Allen 1996; Srinivasan et al. 1998; Arnold et al. 1999; Saleh et al. 2000; Santhi et al. 2001; Abbaspour et al. 2007; Yang et al. 2007; Schuol et al. 2008a, b). Among its interdisciplinary capabilities, SWAT has been specifically used in several studies for the assessment of climate-change effects on watershed hydrology in different regions around the world (Bouraoui et al. 2004; Eckhardt and Ulbrich 2003; Jha et al. 2006; Verbeeten and Barendregt 2007; Chaplot 2007; Marshall and Randhir 2008; Obuobie and Diekkrügerb 2008; Ficklin et al. 2009) because of its capability to easily incorporate the future climate predictions from RCMs as inputs to the model, and to account for the effects of increased CO_2 on plant development and evapotranspiration (Neitsch et al. 2002). Gassman et al. (2007) report 28 SWAT applications in the literature with a primary scope of assessing climate-change impacts.

SWAT has also been used extensively in the context of projects supported by various European Commission (EC) agencies (Gassman et al. 2007). Several models, including SWAT, were used to quantify the impacts of climate change for five different watersheds in Europe within the Climate Hydrochemistry and Economics of Surface-water Systems (CHESS) project, which was sponsored by the EC Environment and Climate Research Programme (CHESS 2001).

Recharge models should incorporate the response of plants to both elevated temperature and atmospheric CO_2 to enable the recharge significance of such physiological changes to be assessed (Holman et al. 2011). The impact of CO_2 on leaf stomatal conductance is computed by SWAT assuming a 40 % reduction in leaf conductance when the atmospheric CO_2 concentration is doubled, as found by Morison and Gifford (1983).

For calculation of evapotranspiration, SWAT takes into account variations of radiation-use efficiency, plant growth, and plant transpiration due to changes in atmospheric CO_2 concentrations, which is essential for any study of CO_2-induced climate change. Conversion of intercepted light into biomass is simulated assuming a specific radiation-use efficiency (RUE) for each plant species. The RUE quantifies the efficiency of a plant in converting light energy into biomass and is assumed to be independent of the plant's growth stage. The RUE values are adjusted in SWAT as a function of CO_2 concentrations, following the approach developed by Stockle et al. (1992). The effect of increasing vapour-pressure deficit, which can result in decreased RUE, is factored into the RUE adjustment.

The Penman-Monteith method is the method recommended by the FAO (Food and Agriculture Organisation of the United Nations) for reference-crop potential evapotranspiration (ET_0) calculation, and has a strong likelihood of correctly predicting ET_0 in a wide range of locations and climates (Allen et al. 1998). This is the method that uses more physical parameters: daily maximum and minimum air temperature, solar radiation, wind speed and humidity are required as inputs. Therefore, it was chosen from the different ET_0 estimation methods incorporated into the SWAT model. SWAT uses a modified version of the Penman-Monteith method based on the methodology described by Stockle et al. (1992).

The way of estimating groundwater recharge by SWAT and most water-budget models is the indirect or "residual" approach, whereby all of the variables in the water-balance equation except the recharge are measured or estimated, and recharge is set equal to the residual value (Scanlon et al. 2002). The major limitation of this approach is that the accuracy of the recharge estimate depends on the accuracy with which the other components in the water-budget equation are measured, and the propagation of errors to the estimate of recharge. This limitation is critical when the recharge rate is relatively small, as in arid and semi-arid regions. However, if the water balance is calculated on a daily time-step, precipitation on a single day (when it occurs) usually greatly exceeds evapotranspiration, and the error in the recharge estimate reduces. Furthermore, error propagation significantly decreases when using a short time-step, while averaging over longer time periods (monthly or annual time-steps) tends to dampen out extreme precipitation events, those most responsible for recharge events (Scanlon et al. 2002).

Data compilation

Model calibration and validation were based on water monitoring data obtained from gauging stations within the study area (Fig. 2). For each studied watershed, at least one gauging station is present at the watershed outlet. Stream discharge data for these gauges were collected from Augas de Galicia (the Galician Water Management Agency). Daily stream discharge series were obtained by means of long-term stage-discharge rating curves. However, only a few measured discharge data corresponding with peak flow events were used during the rating-curve calibration process, so their reliability for high discharge values is limited and these discharge data should be interpreted with caution. In some watersheds, a second gauging station is present for a smaller sub-basin upstream. The data from these gauging stations were gathered by the University of Santiago de Compostela. Daily and monthly average stream flows were aggregated from 10-min data.

Climate data required by the model are: daily precipitation, maximum, medium and minimum air temperature, solar radiation, wind speed and relative humidity. These daily climatic inputs can be obtained from historical records, and/or generated internally in the model using a weather generator tool. For this study, all the historical climate inputs required for model calibration and validation were obtained from 12 weather stations located in and around the studied watershed, at: Penedo do Galo, Muras, Fragavella, Serra da Faladoira, Malpica, Río do Sol, Mabegondo, Pereiro, Mouriscade, Serra do Faro, Sergunde and Marco da Curra (Fig. 2). The meteorological input data were obtained from Meteogalicia (Galician meteorological service), except for the Muras weather station, which is operated by the University of Santiago de Compostela. Missing data in the historical records were filled by correlation from the nearest weather stations with complete records.

The regional projections of climate change for Galicia used in this study were elaborated by the Spanish meteorological agency (AEMet 2009) based on data from the PRUDENCE project (Table 1). Projections for the emissions scenarios A2 and B2 from 2071 to 2100 were generated and referred to a baseline period from 1961 to 1990.

The soil map used in this study was provided by the Joint Research Centre of the European Commission (Van Liedekerke et al. 2006). It was produced within the framework of the Digital Soil Mapping project. It provides an FAO90 classification for Europe with a spatial resolution of 1 km. Soil properties needed by SWAT (e.g., particle-size distribution, bulk density, organic carbon content, available water capacity, and saturated hydraulic conductivity) were obtained from the literature on the basis of the soil types (González-Prieto et al. 1992; Leirós et al. 2000; García-Corona et al. 2004, Paz-Gonzalez et al. 1997) or by using pedotransfer functions (Tietje and Hennings 1996; Ferrer Julia et al. 2004). Due to its low resolution, the map shows only the dominant soil class for each cell. For the Galician area, the only soil types existing are leptosols, regosols, podzols and histosols. Taking into account that Galician soils in hilly areas are usually shallow soils covering the weathered bedrock and the water has to pass a thickness of rock before reaching the water table, the soils have been represented in the model by an additional layer with a higher bulk density and a lower hydraulic conductivity than the preceding soil layer, in order to reproduce the weathered rock effect on groundwater dynamics, as proposed by Eckhardt and Ulbrich (2003). This assumption implies that a significant portion of groundwater flows laterally as interflow, as proposed for most Galician aquifers by different authors (Soriano and Samper 2000; Soto et al. 2005; Samper et al. 2009b; Raposo et al. 2012).

The land-use map was constructed by the CORINE Land Cover 2000 Project version 9/2007 (European Environment Agency 2007). The CORINE land-cover classification codes were converted to the SWAT land-cover/plant codes, to make a reclassified and aggregated land-use dataset. This map has a spatial resolution of 100 m and has 14 classes of land-use representation for the modeled area in this study: residential high density, residential medium density, industrial, urban commercial, potato, agricultural land-generic, forest evergreen, forest deciduous, pine, forest mixed, range brush, range grasses, corn silage, and pasture. The parameterization of the land-use classes was based on the available SWAT land-use classes and literature research. No variations of land use over time were considered in the model. Although they are possible, the direction of change is unpredictable and probably more related to socio-economic factors than climatic factors.

It is well known that the quality of the digital elevation model (DEM) will have a strong influence on the final output of the hydrological model (Defourny et al. 1999).

Table 1 List of PRUDENCE project members and the RCMs, driving-GCMs and emissions scenarios used in this study

Research Center	RCM	GCM	Emission scenario		Reference
			A2	B2	
Centre National de Recherches Météorologiques (CNRM)	ARPEGE	HadAM3H	*	*	Gibelin and Déqué 2003
Denmarks Meteorologiske Institut (DMI)	HIRHAM	HadAM3H	*	*	Christensen et al. 1996
Helmholtz-Zentrum Geesthacht (GKSS)	CLM	HadAM3H	*		Steppeler et al. 2003
Hadley Centre (HC)	HadRM	HadAM3H	*		Hudson and Jones 2002
Koninklijk Nederlands Meteorologisch Instituut (KNMI)	RACMO	HadAM3H	*		Lenderink et al. 2003
Max Planck Institute (MPI)	REMO	HadAM3H	*		Jacob 2001
Swedish Meteorological and Hydrological Institute (SMHI)	RCAO	HadAM3H	*	*	Döscher et al. 2002
		ECHAM4	*	*	
Universidad Complutense de Madrid (UCM)	PROMES	HadAM3H	*	*	Castro et al. 1993

DOI 10.1007/s10040-012-0922-7

A 50-m resolution DEM was used in this study, generated from the contours lines and three-dimensional (3D) elements of basic cartography of the 1:5000 Galician map (SITGA 2010). The stream network and subwatersheds were delineated with ArcSWAT using the DEM. HRUs were created automatically with ArcSWAT within each subwatershed, as a function of the dominant land use, soil types and slope within a given subwatershed.

The management operations were based on default assumptions provided by the SWAT2000 database, developed by Di Luzio et al. (2002). Most of the territory in Galicia-Costa is covered by forest where a low level of management is performed. For agricultural lands, the management operations generally consist simply of planting, harvesting, and automatic fertilizer applications. In some cases, minor modifications were made to improve the management data, like the consideration of large potato fields in the Anllóns basin and silage cornfields in the Deza basin, and the specific-heat units and operational dates for this crop in Galicia (Bande-Castro et al. 2010). However, the relevance of these modifications is small, since the management assumptions have only minor impact on the SWAT hydrological estimates.

Model setup

The model parameterization was derived using the GIS interface for SWAT (Di Luzio et al. 2002). The threshold area of flow accumulation required for the automatic stream network definition was selected depending on the size of each watershed and the desired model detail. A threshold area of 3 km^2 was selected for defining the stream network in the biggest basin (Deza), while a threshold area of only 1.5 km^2 was considered in the smallest one (Mera). Thus, the whole modeled area was divided into 134 subwatersheds and 1,525 HRUs (Anllóns: 47 sub-basins and 507 HRUs; Landro: 20 sub-basins and 270 HRUs; Deza: 37 sub-basins and 406 HRUs; Mera: 30 sub-basins and 342 HRUs).

Regarding land uses, forests cover 36.8 % of the modeled area, crops (mainly corn silage and potato) cover 38.8 % of the area, and range (brush and grasses) covers 23.7 % of the modeled area. Residential and industrial areas only represent 0.7 % of the territory. Regarding soil classes, the dominant soils in the modeled area of Galicia-Costa are regosols (59.0 % of modeled area); leptosols represent 37.0 % of the modeled area; while histosols and podzols are less than 4 % of the modeled area. These percentages are similar to those corresponding to all Galicia-Costa, thus the modeled area can be considered to be representative of the whole district.

Finally, three different slope groups were considered for the HRU definition: less than 10 %, from 10 % to 20 %, and more than 20 %. The curve-number value assigned to each land cover was affected by the slope range of the HRU according to the equation developed by Williams (1995).

The simulation time period varies for the different basins from 2 to 6 years, depending on the availability of meteorological data; a first period was used as a warm up and not included in the analysis. A 1-year validation period was performed during 2010 (Table 2).

Model calibration and validation

Calibration effort was focused on increasing the SWAT model's ability to predict stream flows and to fit the measured and modeled discharge rates. The models were calibrated with Augas de Galicia discharge data from gauging stations 438 (Landro River), 443 (Mera River), 485 (Anllóns River) and 552 (Deza River), located near the mouth of each river. For the Anllóns, Landro and Deza rivers there is a second gauging station located upstream (Fig. 2). In the basins where there is only one stream-flow gauging station, the model was calibrated at the outlet of the watershed and results were processed by sub-basin. When there was more than one gauging station on a river, the model was successively calibrated, starting with the sub-basins upstream of the first gauging station and using its discharge series for fitting the model, and ending with the sub-basins located between the two gauging stations and using the discharge series recorded at the second gauging station for fitting the model.

The calibration process involved changes in parameter values to minimize the deviation between observed and simulated values. Table 3 shows the final calibrated values for the main parameters which were changed from the default values: soil evaporation compensation factor (ESCO); Manning's n value for the tributary channels (Ch_N1); average slope length (SLSUBBSN); average slope steepness (HRU_SLP); Manning's n value for overland flow (OV_N); lateral flow travel time (Lat_-Time); maximum canopy storage (Canmx); Manning's n value for the main channel (Ch_N2); groundwater delay time (GW_delay); baseflow alpha factor (α_Bf); threshold depth of water in the shallow aquifer for return flow to occur (Gwqmn); threshold depth of water in the shallow aquifer required to occur movement of water by capillarity from the shallow aquifer to the root zone or to direct plant uptake (Revapmn); and deep aquifer percolation factor (Rechrg_DP). These parameters are described in Neitsch et al. (2004). In order to reproduce the large quantity of lateral flow observed in most of the catchments in Galicia-Costa, a low value of SLSUBBSN was required. The high values of Manning's n are related to the abundant vegetation (both in the river channels and on land) that there is in a wet and temperate area such as Galicia. The low groundwater delay time is consistent with the rapid response to wet episodes observed in the hydrographs in Galicia-Costa, while relatively low values of α_Bf are responsible for the observed smooth decline of the water table during dry periods. Calibrated values of α_Bf are consistent with those obtained from a different model for the same or other catchments in Galicia-Costa (Raposo et al. 2012). Finally, the deep aquifer percolation factor was always fixed at zero, since there is not any deep confined aquifer in the district.

Table 2 Evaluation of the hydrological goodness-of-fit in the studied basins(calibration and validation parameters defined in the text)

	Basin	Landro River		Deza River		Anllóns River		Mera River
	Gauging station	Muras	Landro	Abeleda	Deza	Carballo	Anllóns	Mera
	Warm-up	31 Mar 05 to 30 Jun 05	31 Mar 05 to 25 Oct 06	1 Oct 01 to 9 Feb 07	1 Oct 01 to 31 Jan 04	1 Sep 06 to 31 Jan 09	1 Sep 06 to 31 Oct 06	26 May 06 to 31 Mar 07
Calibration	Calibration period	1 Jul 05 to 31 Dec 09	26 Oct 06 to 31 Dec 09	10 Feb 07 to 31 Dec 09	1 Feb 04 to 31 Dec 09	1 Feb 09 to 31 Dec 10	1 Nov 06 to 31 Dec 09	1 Apr 07 to 31 Dec 09
	Coeff. R^2	0.78	0.81	0.82	0.76	0.81	0.85	0.78
	Nash-Sutcliffe	0.73	0.79	0.82	0.76	0.74	0.77	0.71
	Relative Nash-Sutcliffe	0.89	0.84	0.91	0.89	0.79	0.85	0.90
	Measured/ Modeled ratio	0.91	1.11	0.99	0.93	0.85	0.82	0.86
Validation	Validation period	1 Jan 10 to 3 Dec 11	1 Jan 10 to 31 Dec 10	1 Jan 10 to 31 Dec 10	1 Jan 10 to 31 Dec 10	–	1 Jan 10 to 31 Dec 10	1 Jan 10 to 31 Dec 10
	Coeff. R^2	0.80	0.74	0.83	0.80	–	0.82	0.68
	Nash-Sutcliffe	0.77	0.71	0.78	0.73	–	0.82	0.65
	Relative Nash-Sutcliffe	0.89	0.83	0.85	0.86	–	0.83	0.78
	Measured/ Modeled ratio	1.02	0.87	1.11	0.86	–	0.98	0.88

As a first step, a sensitivity analysis was performed, in order to identify the parameters most sensitive to flow generation. The SWAT model includes an automated calibration procedure that was implemented by Van Griensven (2005). The autocalibration option in SWAT provides a powerful, labor-saving tool that can be used to substantially reduce the frustration and uncertainty that often characterizes manual calibration (Van Liew et al. 2005). The most sensitive parameters were automatically adjusted to obtain the range of values that provided a good fit. After that, they were consecutively adjusted manually by trial and error to fit the daily measured flow-rate series. To that end, they were allowed to vary between the values considered acceptable by the model (Neitsch et al. 2004). Finally, monthly and annual stream flows during the calibration period were checked, to assure proper annual and seasonal variability.

The statistical criteria used to evaluate the hydrological goodness-of-fit were the coefficient of determination (R^2) and the model efficiency or Nash-Sutcliffe coefficient (E) (Nash and Sutcliffe 1970). Both coefficients are highly influenced by the good matching records of high values. 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 was to evaluate the groundwater recharge responsible for the stream baseflow.

Figures 4, 5, 6, 7 show the fit obtained for modeled versus measured flow rates in the studied basins and sub-basins during the calibration period and the validation period. The model reproduces the measured stream discharge fairly well during low discharge periods, while a mismatch is observed for many of the peak flow events. However, a comparison of the annual stream discharges provided by Augas de Galicia with the annual rainfall in their corresponding catchments suggests that the rating curves developed by Augas de Galicia may overestimate the stream discharge during peak flow events, while the SWAT modeled discharge seems more realistic. The correlation coefficient for observed versus predicted daily stream flow during the calibration period for the four basins ranges from 0.73 to 0.82. The model efficiency varies from 0.71 to 0.82. The best model fit is obtained for low-flow conditions, with the relative efficiency criteria varying between 0.83 and 0.91 (Table 2). An internal validation of the model's predictive ability within the study watersheds was also conducted using the last year of the discharge rate time-series. For the validation period, the correlation coefficients obtained in the four basins range from 0.68 to 0.83, the model efficiency varies from 0.65 to 0.79, and the relative efficiency criteria range from 0.78 to 0.86 (Table 2).

Since SWAT is a semi-distributed model, it is not suited to accurately reproducing groundwater hydrographs observed in specific wells. Furthermore, the groundwater level is not currently included in any of the SWAT output files, therefore observed groundwater hydrographs cannot be used for model calibration. However, the equations used to calculate the change in groundwater level are

Table 3 Calibrated parameters which were changed from the default values (parameters defined in the text)

Basin	Landro River		Deza River		Anllóns River		Mera River
Gauging station	Muras	Landro	Abeleda	Deza	Carballo	Anllóns	Mera
ESCO	0.95	0.75	0.674	0.674	0.755	0.755	0.95
CH_N1	0.04	0.04	0.17	0.17	0.17	0.17	0.1
SLSUBBSN (m)	10	10	10	10	10	10	10
HRU_SLP*	0.061/0.151/0.355	0.058/0.146/0.302	0.065/0.2/0.35	0.065/0.2/0.35	0.03/0.1/0.25	0.03/0.1/0.25	0.054/0.15/0.32
OV_N	0.4	0.4	0.45	0.45	0.45	0.45	0.45
Lat_Time (days)	3	3	6	6	4	4	5
Canmx (mm)	1.2	2	1	1.29	1.29	1.29	1.29
CH_N2	0.075	0.075	0.17	0.17	0.014	0.014	0.05
GW_Delay (days)	5	5	5	5	2	2	2
α_Bf (day^{-1})	0.018	0.01	0.04	0.01	0.015	0.015	0.03
Gwqmn (mm)	10	10	0	0	0	0	10
Revapmn (mm)	10	10	80	80	1	1	1
Rechrg_DP	0	0	0	0	0	0	0

*Value of HRU_SLP parameter for each slope range

included in SWAT and water-table level can be externally updated daily using the following equation:

$$h_\mathrm{i} = \left(h_{\mathrm{i}-1} \times \mathrm{e}^{-\alpha\_Bf \times \Delta t}\right) + \frac{w \times \left(1 - \mathrm{e}^{-\alpha\_Bf \times \Delta t}\right)}{800 \times \mu \times \alpha\_Bf} \qquad (1)$$

where h_i and $h_{\mathrm{i}-1}$ are the water-table elevation above the aquifer discharge level on days i and i–1 respectively (m), α_Bf is the baseflow recession constant, Δt is the time-step (1 day), w is the amount of recharge entering the shallow aquifer on day i (mm H_2O), and μ is the specific yield of the shallow aquifer (m/m).

Once the daily water-table elevation series has been calculated, it can be used for model validation against observed groundwater hydrographs. Figure 8 shows the fit obtained for modeled versus measured groundwater levels in a well located inside the Deza basin and monitored over the period 2007–2009. The baseflow recession constant for the corresponding sub-basin where the monitoring well is located was found to be equal to 0.04 from the calibrated model; and the average specific yield of the shallow aquifer was assumed equal to 0.03; in this way, the correlation coefficient obtained is 0.68. This fit can be considered quite good, taking into account the limitations of the model for predicting groundwater levels.

Incorporating climate change projections: results and uncertainty

Assuming accurate estimates of the hydrological-cycle components, SWAT was used to evaluate the impact of changes in climate and atmospheric CO_2 concentration on hydrological processes.

A control scenario for the period 1961–1990 and two warming scenarios for the period 2071–2100 were run using the models, previously calibrated with baseline conditions, to best simulate conditions in the watershed. Climatic data used in these three scenarios derived from regional projections elaborated by AEMet (2009). The control scenario used an atmospheric CO_2 concentration of 330 ppm. The first warming scenario (A2) assumed an

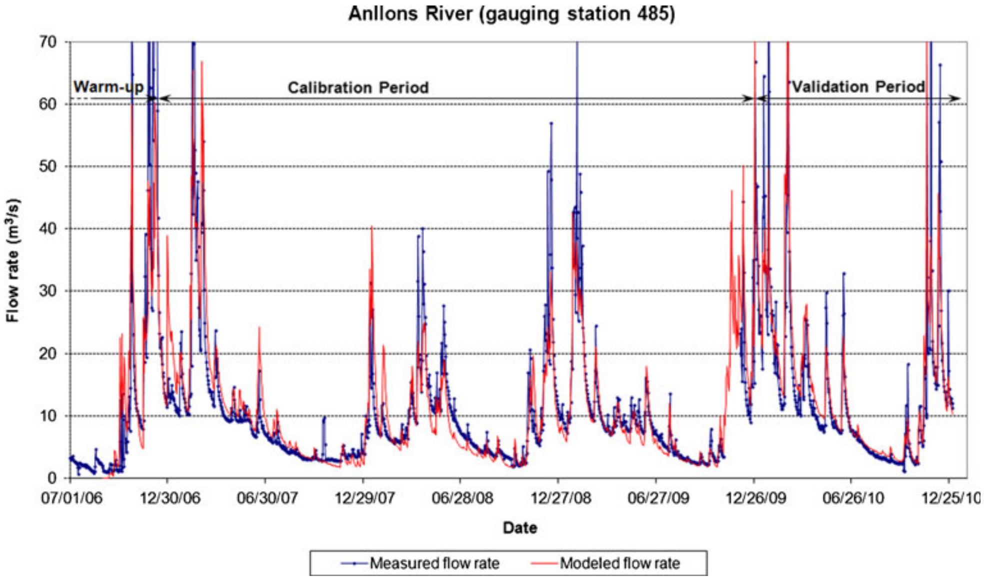

Fig. 4 Modeled versus measured flow rates in the Anllóns River (gauging station 485) during the calibration period and the validation period

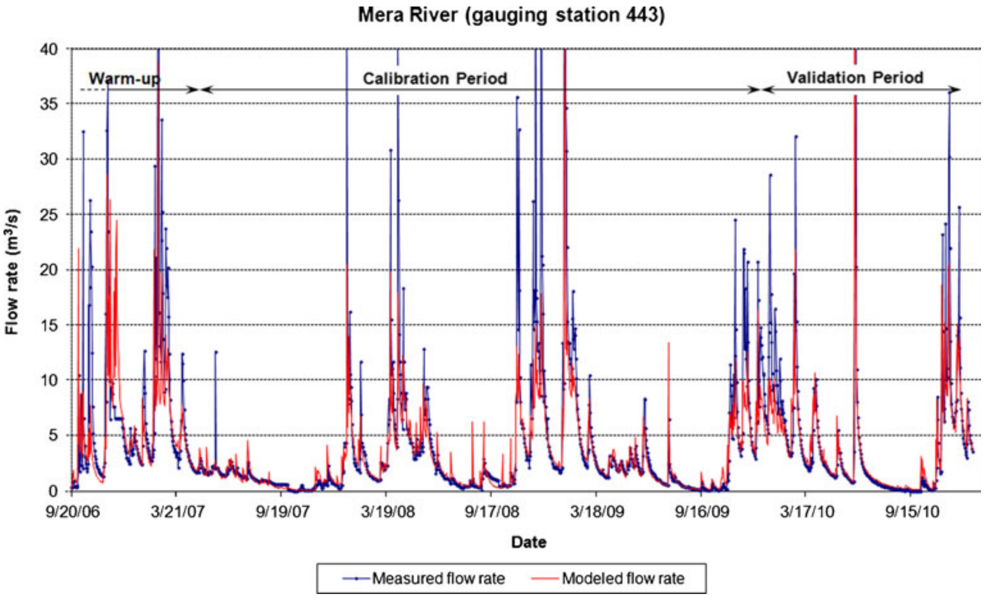

Fig. 5 Modeled versus measured flow rates in the Mera River (gauging station 443) during the calibration period and the validation period

atmospheric CO_2 concentration of 635 ppm and the second warming scenario (B2) assumed an atmospheric CO_2 concentration of 531 ppm.

It is important that impact models be calibrated across as wide a range of historic observations and/or climate conditions as possible, to increase the possibility of model robustness for future conditions (Holman et al. 2011). A longer historic series of monthly flow rates since 1970 is available for the studied rivers, allowing a complementary evaluation of the robustness of the model and climate projections. This comparison was made using average monthly discharge values, since results from RCMs do not reproduce the climate of an actual year but rather the average value (Fig. 9).

Following the suggestions of Leung et al. (2003b), the uncertainty introduced by using outputs from different RCMs on the hydrological response to climate change was taken into account using PRUDENCE ensemble outputs for the four studied basins. Generally, Atlantic climatic conditions are well predicted by the RCMs that were used; the Nash-Sutcliffe criteria ranges from 0.57–0.95 for most RCMs (Table 4). However, Cantabrian climatic conditions are poorly modeled, especially during the winter, and therefore measured river discharge cannot be reproduced with any accuracy. Only results from HIRHAM, HadRM3H and CLM RCMs obtained a good fit to discharge.

For the same RCM, the HadAM3H-driven RCAO simulations (explained in Table 1) always reproduce better the river discharges than the ECHAM4-driven RCAO simulations. This larger bias of the ECHAM4 model for simulating precipitation in southern Europe is described by Räisänen et al. (2004).

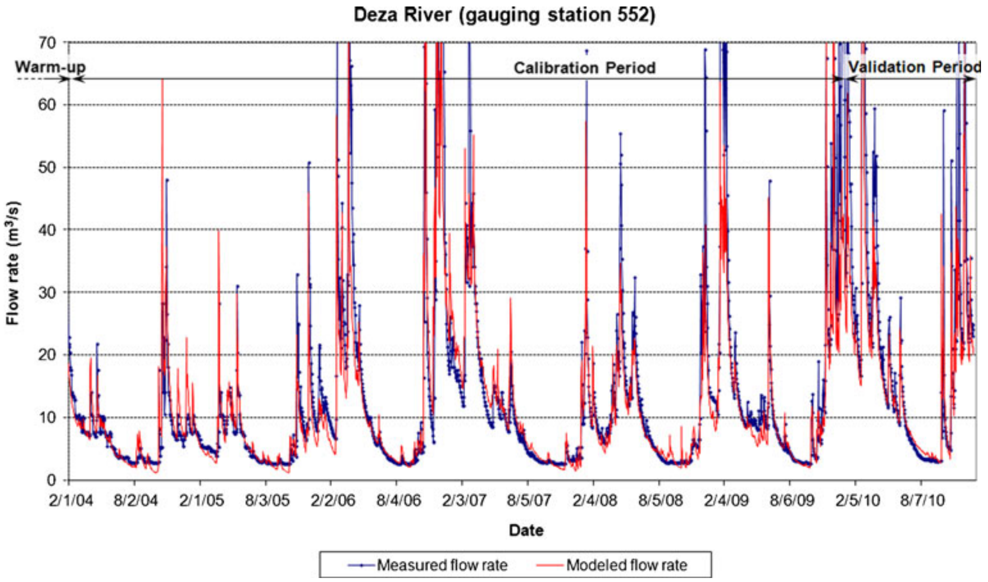

Fig. 6 Modeled versus measured flow rates in the Deza River (gauging station 552) during the calibration period and the validation period

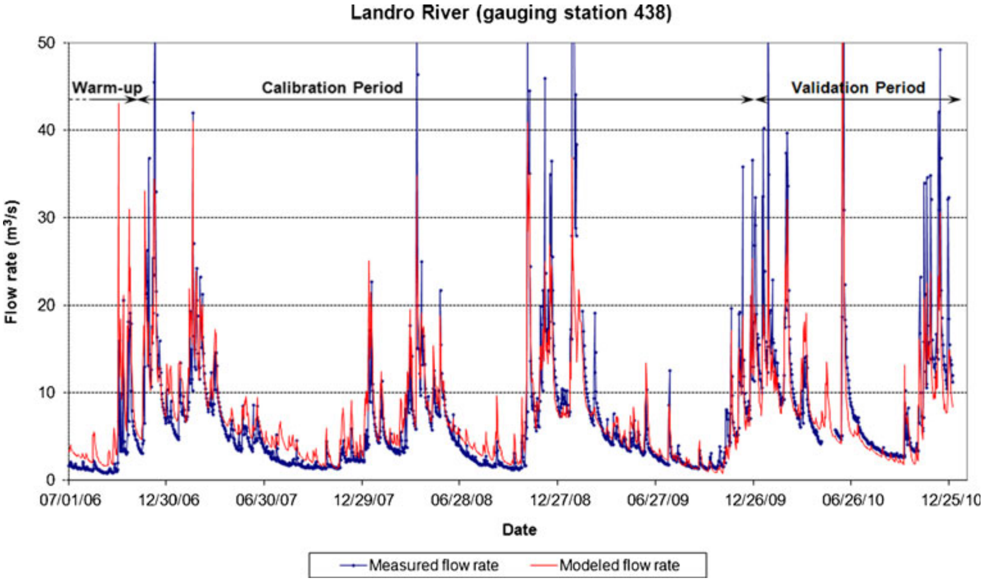

Fig. 7 Modeled versus measured flow rates in the Landro River (gauging station 438) during the calibration period and the validation period

Due to the large amount of data resulting from nine different models with three different scenarios in the four studied basins, results have been summarized in Table 5 as the average variation of the two warming scenarios versus the control scenario. The standard deviation reveals the variability of the results due to the use of different GCMs and RCMs and gives a range of confidence in the models' predictions. Figure 10 shows an example of the expected changes in the discharge characteristics of the hydrographs under the A2 and B2 scenarios. Stream discharge significantly decreases, especially in spring and autumn, due to the predicted decrease of precipitations. Base-flow in summer also decreases due to the reduction of groundwater recharge. Precipitation mainly concentrates in winter, when almost no changes are expected in the stream discharge.

Due to the lower water entry into the system owing to the decline in annual precipitation predicted by all RCMs that were used (ranging from −3.84 to −27.49 % for A2 scenarios and from −0.80 to −13.05 % for B2 scenarios) a consequent absolute decrease in all components of the water balance is expected, except in the run-off, which slightly increases due to the concentration of rainfall in a smaller number of more intense events during the winter (Table 5). However, a different relative change of each component of the water balance is predicted. The decrease in groundwater recharge is smaller than the decrease in precipitation, while water losses by evapotranspiration decline at a higher rate. In fact, a slight increase in the recharge rate is expected, although it would not be enough to compensate for the precipitation decline. This is a

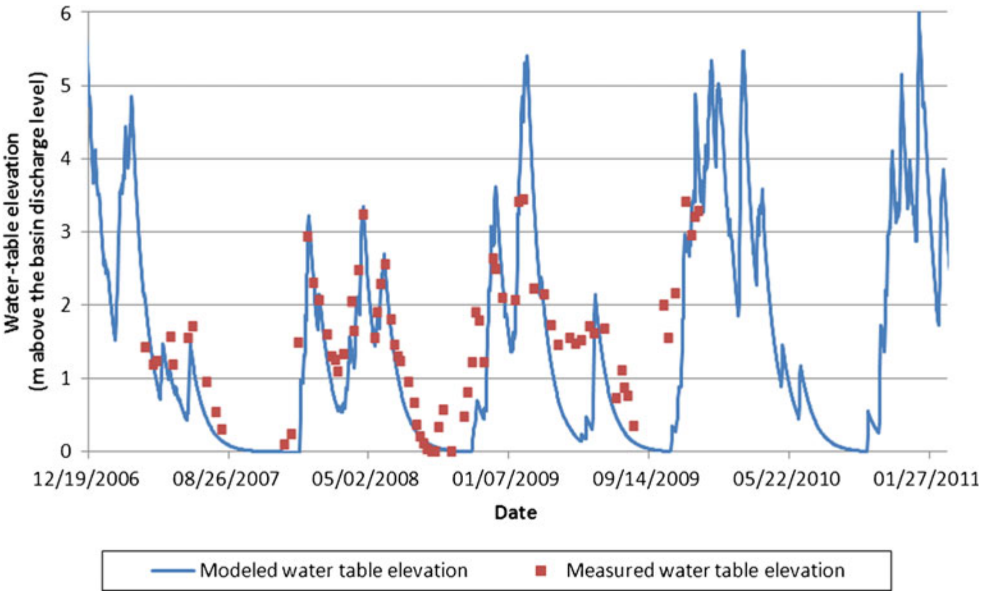

Fig. 8 Modeled versus measured water-table level in a monitored well in the Deza basin, used for model validation

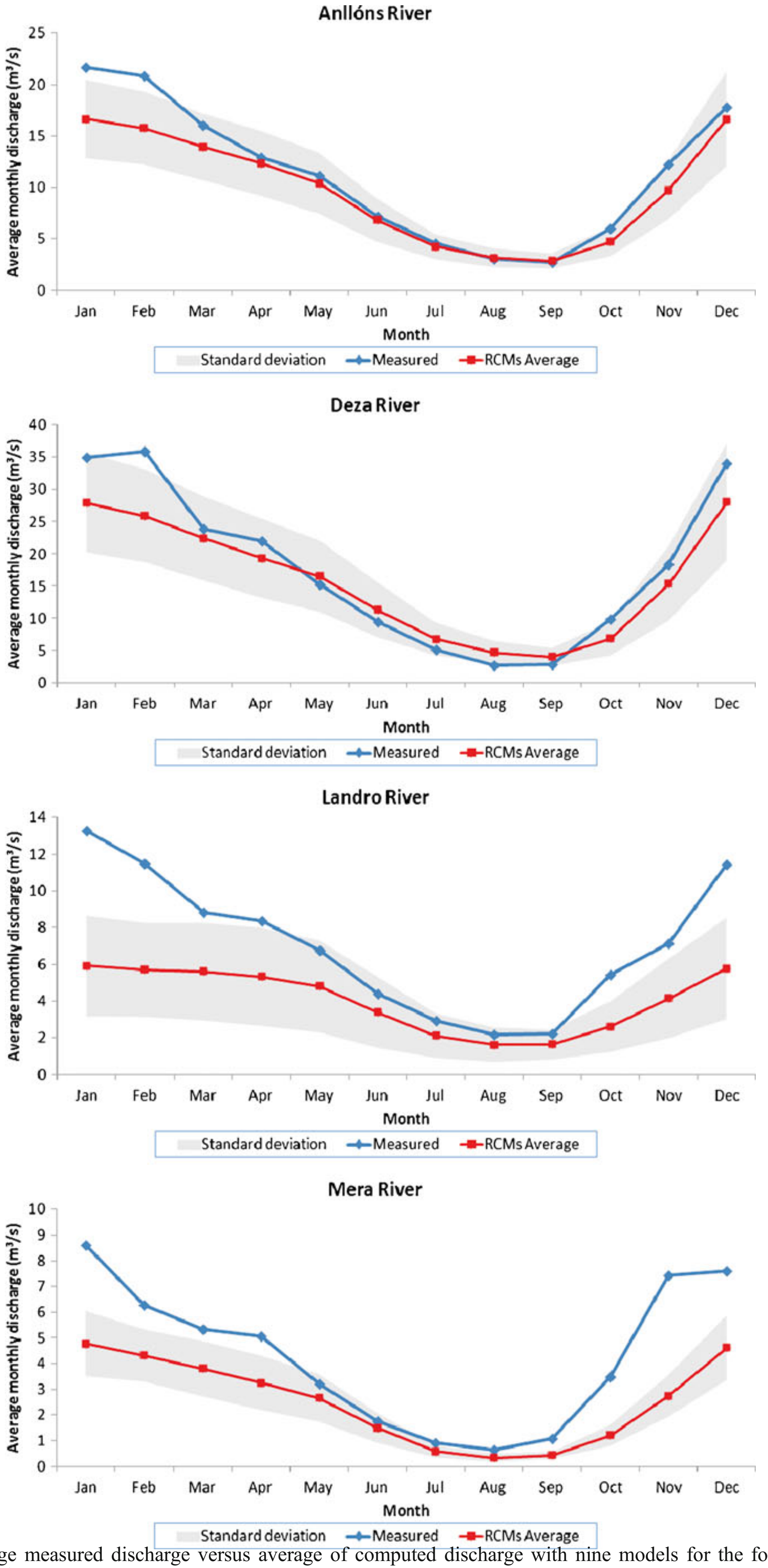

Fig. 9 Monthly average measured discharge versus average of computed discharge with nine models for the four studied river basins during the control period 1970–1987

Table 4 Evaluation of model efficiency for calculated discharge rates during the control scenario (the numbers show the Nash-Sutcliffe criteria for each model and the average for all models, and the models are explained in Table 1)

	River			
Model	Anllóns	Deza	Landro	Mera
ARPEGE/IFS	0.77	0.63	−0.47	−0.31
HIRHAM-HadAM3H	0.59	−0.39	0.64	0.72
PROMES-HadAM3H	0.79	0.95	−2.95	−0.15
RCAO-HadAM3H	0.57	0.89	−0.52	−0.06
RCAO-ECHAM4	0.01	0.57	−0.98	−0.37
HadRM3H-HadAM3H	0.83	0.93	0.71	0.62
CLM-HadAM3H	0.90	0.69	0.74	0.49
REMO-HadAM3H	0.85	0.82	−0.26	0.50
RACMO2-HadAM3H	0.94	0.95	−0.06	0.53
RCMs Average	0.87	0.87	−0.04	0.31

consequence of indirect changes to evapotranspiration caused by climate change such as the partial closure of stomatal apertures on plant leaves in response to increased CO_2 concentration (Field et al. 1995). In order to confirm this assertion, additional testing was carried out, without considering the CO_2 effect on plant response, and both results (with and without CO_2 increase) were compared. Without considering the effects of CO_2 on plants, an average decrease in recharge rate of −13.25 % for the A2 scenario and −8.66 % for the B2 scenario was modeled, compared to slight increases in average recharge rate of 0.40 and 1.99 % respectively when enhanced plant efficiency was considered. In the water balance, this relative increase in recharge rate is mainly compensated for by lower water losses from evapotranspiration (13.69 and 8.43 % lower, respectively, for A2 and B2 scenarios when the CO_2 effect on plant efficiency is considered). Therefore, comparison of results indicates that about 11.92–9.82 % of the groundwater recharge in Galicia-Costa over the period 2070–2100 could be attributed to greater plant efficiency due to elevated CO_2 concentration. This significant influence on plants must be always considered when assessing the impacts of climate change.

On an annual basis, a moderate decrease in recharge of −12.68 % for the A2 scenario and −6.03 % for the B2 scenario is expected for the period 2071–2100 compared to 1961–1990, similar to other studies in northern Spain (Candela et al. 2009; Samper et al. 2007; Samper et al.

Table 5 Results of warming scenarios expressed as average variation versus the control scenario and standard deviation in each studied basin (the numbers give the relative change in %, with the absolute change given in *parentheses*, in mm/year or days/year (*last four rows*). *SD* standard deviation

Average variation vs. control scenario	Landro Basin		Deza Basin		Anllóns Basin		Mera Basin	
	Average	SD.	Average	SD	Average	SD	Average	SD
Δ Precipitation in A2	−13.35	5.52	−15.68	5.51	−11.38	5.10	−12.50	5.19
	(−150)	(61)	(−225)	(77)	(−139)	(54)	(−153)	(55)
Δ Precipitation in B2	−8.08	4.44	−9.72	3.07	−6.69	2.54	−7.51	3.95
	(−78)	(48)	(−120)	(19)	(−75)	(32)	(−84)	(42)
Δ ET_0 in A2	−15.71	3.68	−14.62	5.28	−17.03	3.83	−14.14	4.68
	(−79)	(25)	(−74)	(29)	(−90)	(28)	(−75)	(29)
Δ ET_0 in B2	−10.94	3.11	−14.06	4.00	−11.90	3.03	−9.48	3.70
	(−53)	(18)	(−71)	(23)	(−64)	(20)	(−50)	(22)
Δ Recharge in A2	−10.06	11.97	−17.43	7.55	−11.62	9.38	−11.59	9.43
	(−37)	(40)	(−93)	(42)	(−39)	(27)	(−35)	(25)
Δ Recharge in B2	−4.90	12.66	−8.50	5.98	−4.67	4.72	−6.07	10.80
	(−13)	(36)	(−36)	(28)	(−14)	(15)	(−15)	(26)
Δ Run-off in A2	1.56	25.02	−8.91	16.24	150.44	161.33	−8.14	8.09
	(−1)	(2)	(−13)	(14)	(26)	(30)	(−7)	(6)
Δ Run-off in B2	25.78	51.57	5.81	13.92	192.42	239.78	3.40	13.31
	(1)	(1)	(7)	(8)	(14)	(17)	(1)	(6)
Δ Lateral flow in A2	−11.64	7.79	−15.45	6.55	−11.01	7.63	−11.80	7.59
	(−33)	(23)	(−46)	(20)	(−37)	(23)	(−37)	(21)
Δ Lateral flow in B2	−6.05	7.89	−8.23	4.39	−4.22	3.29	−6.95	7.88
	(−14)	(20)	(−20)	(11)	(−12)	(10)	(−19)	(20)
Δ Max. annual period without recharge in A2	37.78	18.96	20.19	11.93	23.16	10.68	35.27	15.27
	(65)	(47)	(39)	(26)	(36)	(15)	(55)	(19)
Δ Max. annual period without recharge in B2	17.89	10.49	12.14	10.42	13.09	7.39	23.06	15.71
	(34)	(12)	(22)	(17)	(22)	(11)	(38)	(21)
Δ Days/year without recharge in A2	5.05	7.85	6.55	3.03	17.80	6.62	9.62	3.48
	(13)	(9)	(18)	(8)	(29)	(12)	(22)	(9)
Δ Days/year without recharge in B2	3.39	3.87	3.94	3.88	12.37	6.54	6.48	4.03
	(9)	(10)	(11)	(10)	(22)	(12)	(15)	(10)

DOI 10.1007/s10040-012-0922-7

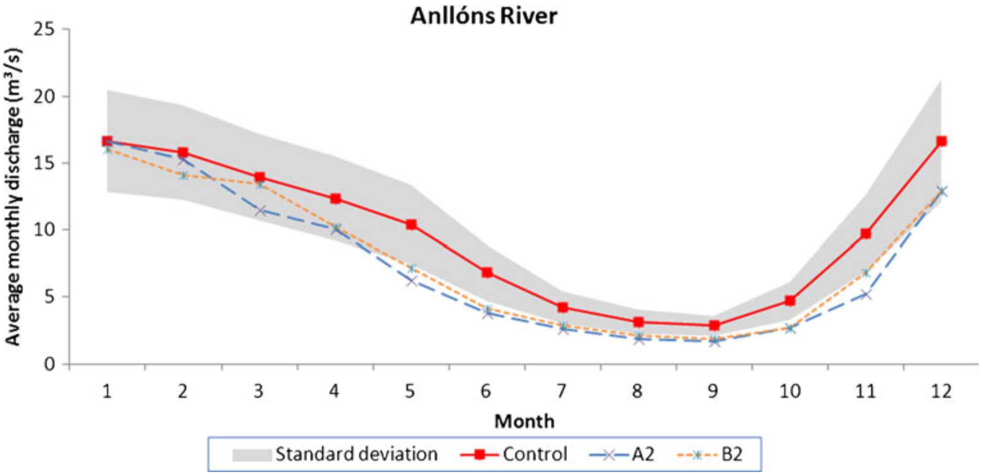

Fig. 10 Monthly average computed discharge during the control period versus average computed discharge under *A2* and *B2* emissions scenarios for the Anllóns River (in order to compare both scenarios, the A2 computed discharge only averages the results from the RCMs ARPEGE, HIRHAM, RCAO and PROMES)

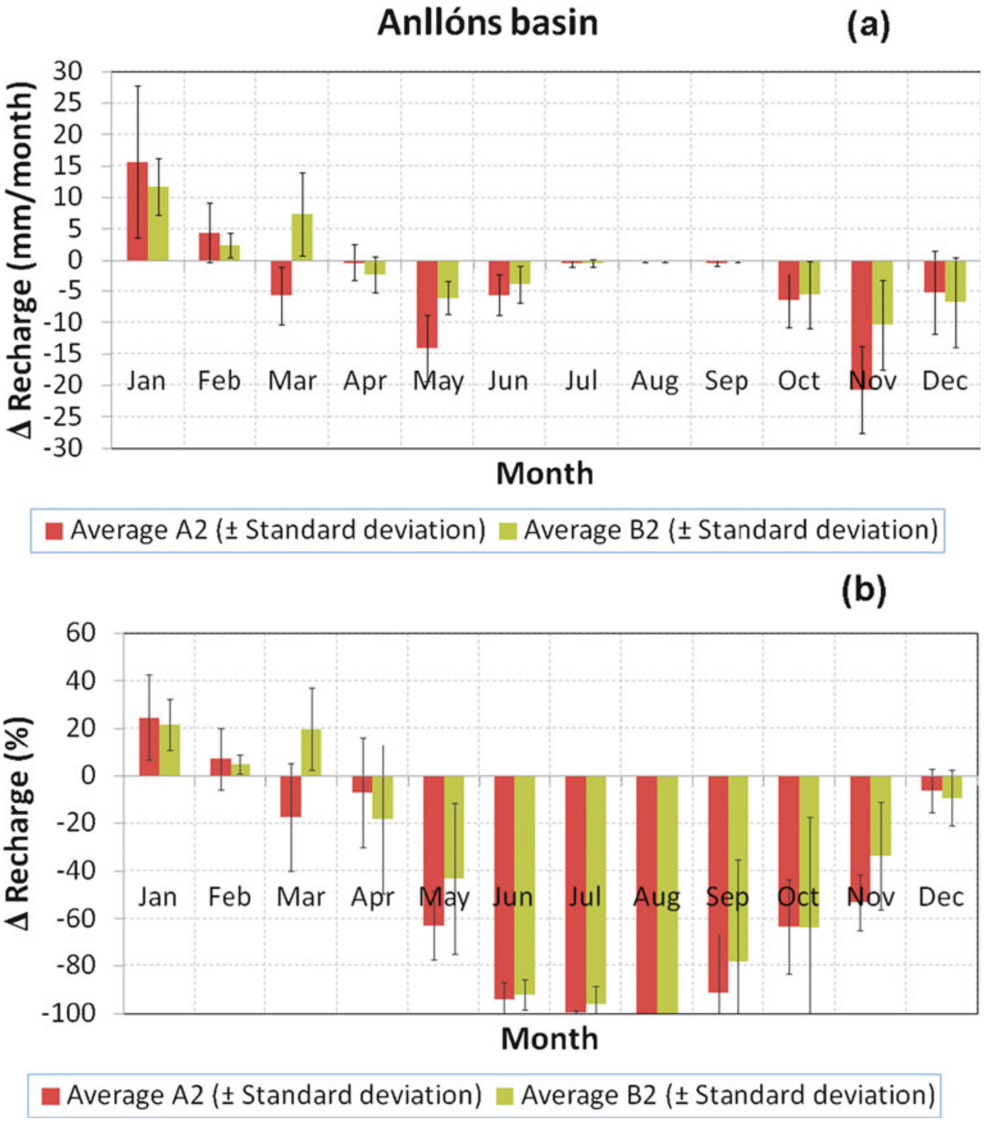

Fig. 11 Average monthly variation of groundwater recharge for scenarios *A2* and *B2* with respect to the control scenario in the Anllóns basin, expressed as absolute changes (**a**) and relative changes (**b**)

2009a; Younger et al. 2002) but significantly lower than estimated by other studies in southern Spain (Aguilera and Murillo 2009; Guardiola-Albert and Jackson 2011; Hiscock et al. 2012). However, uncertainty linked to the climate projections remains relatively large, especially those related to changes in precipitation patterns. Since reduction in precipitation is the main cause of decrease in recharge, these results should be interpreted with caution, especially in the Cantabrian area. Despite the uncertainties in the magnitude of recharge change, shown by the high standard deviation in the results of the different models, the direction of change towards a recharge decrease is clearer (observed in 50 out of 56 models). Europe may be divided into two regions according to their hydrogeological response to climate change: northern Europe, which is likely to experience an increase in recharge, although more concentrated in the winter season; and southern Europe, where an evident decrease in potential groundwater recharge is expected (Hiscock et al. 2012). In this context, Galicia-Costa District may be considered a border region in southern Europe.

While changes in annual recharge rate would be moderate, changes in the temporal distribution of recharge may be still more relevant; groundwater recharge dramatically decreases during the spring–autumn seasons, but increases in the winter season (Fig. 11). There is a decrease in the total number of days a year with groundwater recharge and, due to higher concentration of precipitation in the winter period, those days without groundwater recharge concentrate in a longer dry season. These results are consistent with those obtained for different aquifers in Europe (Candela et al. 2009; Herrera-Pantoja and Hiscock 2008; Jackson el al. 2011; Neukum and Azzam 2012; Hiscock et al. 2012). An increase in the maximum period without recharge may be the clearest effect of climate change on groundwater in Galicia-Costa. The dry season may increase, on average, 29.10 % for the A2 scenario and 16.54 % for the B2 scenario, extending from June to October, in contrast with only 3 months of dry season with monthly infiltration less than 3 mm (from July to September) modeled in the control period. This trend was observed in 55 out of 56 models, and it is significantly higher in the Cantabrian basin that in the Atlantic ones. Taking account of the low storativity of Galician fissured aquifers, this longer summer drought may result in more frequent drying up of most springs and shallow wells that supply drinking water for many rural communities. In general, it is very likely that temporal rainfall patterns through the year will be impacted, with a tendency towards extreme episodes like more persistent droughts and floods. In addition to the impacts on summer water supply, this would have implications for agricultural production, groundwater-dependent ecosystems, management of dams and hydropower production.

If changes in annual recharge are not too severe, as the models predict, current water-supply regimes can be maintained, since current total abstraction is a small percentage of annual recharge (Raposo et al. 2012). However, technical measures must be taken in order to solve the more persistent future problems of water supply during the dry season. Current traditional shallow wells, which pump mainly recharge water from the groundwater-fluctuation zone, may be not enough to ensure water supply in summer, and new deep drilled wells that draw groundwater reserves from the fissured aquifer may be needed.

Conclusions

There is large uncertainty linked to the different climate projections used as inputs, especially in Cantabrian area; however, it can be concluded according to model results that projected annual precipitation decrease will be reflected in a smaller decrease of annual groundwater recharge, partly due to the greater stomatal efficiency of plants in response to increased CO_2 concentration. The CO_2 influence on plant physiology must always be taken into account, since its neglect may lead to an overestimation of recharge decrease by 11.92–9.82 %, depending on the scenario. The models showed an average decrease in annual recharge of 12.68 % for the A2 scenario and 6.03 % for the B2 scenario, with only six models predicting slight increases, and 50 models predicting decreases.

Assuming the model results are correct, the main impact of climate change on Galician groundwater resources will be modification of the temporal pattern of recharge, which would mainly concentrate in the winter season, but dramatically decrease in the spring–autumn seasons. As result, the length of the dry season would increase on average from 29.10 to 16.54 % depending on the emissions scenario. The increase would be significantly greater in Cantabrian basins than Atlantic ones.

That effect may be especially relevant on fractured crystalline-bedrock aquifers with low storativity and short groundwater residence times, like those present in Galicia-Costa and other European regions, which supply drinking water for many rural communities. Furthermore, the shallow wells existing in Galicia are very sensitive to water-table drawdown in summer, aggravating this problem.

Present results provide technical criteria to decision-takers in the application of water-planning measures. A set of structural measures must be implemented in order to avoid future water-supply problems to the quarter of the total population of Galicia-Costa that depends on groundwater. A progressive change in the groundwater uptake facilities that supply water to many villages, which currently are natural springs or shallow dug wells that draw water from the shallow aquifer in the weathered rock, is strongly suggested. Construction of deeper drilled wells that could draw groundwater reserves from the fissured-rock aquifer, less vulnerable to water-table drawdown, is required in order to guarantee the future water supply to that population under the predicted climate-change scenarios.

Acknowledgements This work has been partially funded by the Galician government Xunta de Galicia, within the framework of research project INCITE09 203 072 PR and by the European Regional Development Fund (ERDF). The first author has been granted a F.P.U. fellowship by the Spanish Ministry of Education.

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