Potential impacts of climate change on groundwater supplies to the Doñana wetland, Spain

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Abstract

Climate change impacts on natural recharge and groundwater-wetland dynamics were investigated for the Almonte-Marismas aquifer, Spain, which supports the internationally important Doñana wetland. Simulations were carried out using outputs from 13 global climate models to assess the impacts of climate change. Reductions in flow from the aquifer to streams and springs flooding the wetland, induced by changes in recharge according to different climate projections, were modelled. The results project that the change in climate by the 2080s, under a medium-high greenhouse gas emissions scenario, leads to a reduction in groundwater resources. The reduction in mean recharge ranges from 14% to 57%. The simulations show that there is an impact on hydraulic head in terms of the overall water table configuration with decreases in groundwater level ranging from 0 to 17 m. Most simulations produce lower discharge rates from the aquifer to stream basins, with significant reductions in the larger La Rocina (between -55% and -25%) and Marismas (between -68% and -43%) catchments. Water flows from these two basins are critical to maintain aquatic life in the wetland and riparian ecosystems. Modelled climate-induced reductions in total groundwater discharge to the surface are generally larger than current groundwater abstraction rates. The results highlight that effective strategies for groundwater resources management in response to future climate change are imperative.

1. Introduction

Considered one of the most valuable wetlands in Europe, Spain's Doñana area, an intricate matrix of marshlands and phreatic lagoons covering an area of 270 km^2, is a refuge for millions of migratory birds and several endangered species. However, public and tourist water demands, industrial pollution, and toxic mine drainage place water resources under continuous pressure and pose a serious threat to the biodiversity of the wetland. Within this context of water scarcity, climate change is likely to exacerbate water resource shortages. Consequently, groundwater will become increasingly important in conserving riparian ecosystems and groundwater dependent wetlands. These issues have made the scientific community (Custodio et al. 2007), management authorities (Junta de Andalucía 2009), and environmental organizations (WWF España 2006) consider how policies for the management of the Doñana wetland and its surrounding areas, which have been designated as both a National Park and a UNESCO World Heritage Site, can include climate change mitigation and adaptation measures.

In relation to water resources it is expected that climate change will result in increasing evaporation, more intense periods of precipitation, and more extreme hydrological events such as floods and droughts (IPCC 2007). Global climate models (GCMs) project mean annual increases in temperature of between 1.2 and 7.4°C in the Doñana area for the 2071–2100 time-slice (IPCC 2007). Projections of changes in precipitation are less well constrained and the GCM outputs indicate that there is uncertainty about the sign of the change.

Over the last decade, an extensive amount of research has been published on how climate change might affect different aspects of the hydrological cycle, as reviewed by Bates et al. (2008), and impacts on groundwater resources are receiving greater attention (Dragoni and Sukhija 2008). Most of the research examining groundwater-related climate effects has used physically-based or empirical models to simulate groundwater system response to a change in climate. Whichever approach is adopted, it is necessary to quantify the change in precipitation and temperature under future conditions. This can be done by constructing plausible scenarios that are informed by the range of regional climate model (RCM) and GCM outputs (e.g., Woldeamlak at al. 2007) or by downscaling individual GCM outputs to the catchment scale (e.g., Segui et al. 2010). Few studies of the effects of climate change on groundwater have used ensembles of more than three different scenarios in their assessment (Eckhardt and Ulbrich 2003; Woldeamlak et al. 2007; Goderniaux et al. 2009; Jackson et al. 2011).

Relatively few studies have examined the effects of climate change on groundwater resources in Spain. Manzano et al. (1998) estimated decreases in recharge of up to 16% for Mallorca for the period 1992–2040 compared to 1974–1988. Younger et al. (2002) simulated decreases in mean recharge of up to 8% and 16% for aquifers in Cataluña and Mallorca, respectively, by 2036–2045 relative to pre-1995 values. Custodio et al. (2007) performed a preliminary analysis to quantify the effects of climate change on the Doñana area from empirical formulas of evapotranspiration. More recently, Aguilera and Murillo (2009) examined twentieth century recharge rates and identified decreasing trends in decadal mean recharge for four karstic aquifers in Alicante. Candela et al. (2009) applied two different climatic scenarios developed by the Intergovernmental Panel on Climate Change (IPCC 2000) to examine the effects of climate change and management scenarios on the Inca-Sa Pobla coastal aquifer, Mallorca and its associated wetland. GCM outputs were used to quantify recharge and drive a numerical model of the aquifer, for which overall decreases in natural recharge ranging from 4% to 21% by 2025 were simulated. In Doñana, Guardiola-Albert et al. (2009) investigated how groundwater outputs vary depending on the occurrence of dry, medium, or wet years.

Considering climate change pressures, and the importance of managing water resources effectively for ecosystem services within the Doñana area, this paper addresses the issue of GCM uncertainty in an evaluation of the impact of climate change on groundwater resources. First, we examine the potential impacts on groundwater recharge in the Almonte-Marismas aquifer. Second, we analyse the impact of a change in climate of southern Spain on the hydrogeological system, in particular on the groundwater discharge into the streams flowing into the marshland. The study used outputs from 13 GCMs (Table 1) available from the IPCC Data Distribution Centre for the 2080s under the A2 emission scenario (IPCC 2000) to generate future downscaled sequences of precipitation and potential evaporation (PE) by perturbing historic sequences of these variables. This provides an indication of the level of confidence to be attached to the results of the impact assessment. These projected climatic variables were used to drive distributed recharge and groundwater flow models and calculate changes in rainfall recharge, groundwater levels in the aquifer and in groundwater discharge into the streams flowing into the marshland.

2. Study area

2.1. Location and physiography

The Doñana wetland, located in the south-west Iberian Peninsula (Figure 1a), is considered one of the most important in Spain (Serrano et al. 2006). It extends along the coast between the estuaries of the Guadalquivir and Tinto rivers, and inland to the uplands of “El Aljarafe” (Sevilla). It covers an area of approximately 1000 km^2 within which there are regions with different levels of environmental protection. Apart from the marshland the area has a large number of small, temporary lagoons (Sousa and García Murillo 1999).

At the same time, the Doñana region constitutes an area containing a wide variety of competing water resource demands necessary to maintain agriculture, industry, mining, and tourism. Since the late 19th century different kinds of human activity have significantly changed the natural environment. The area of marshland has decreased from 1400 km^2 to the 270 km^2 that remain in a semi-virgin state today (Rodríguez-Rodríguez et al. 2006).

The topography of the region falls from approximately 150 m above sea level (m aSL) in the north to less than 1 m aSL in the marshland area near the coast in the south. To the south fossil sand dunes form coastal cliffs over 100 m high that are retreating due to coastal erosion. Rivers and streams flow from the higher regions in the north towards the marshland as does the Guadiamar River, which drains a complex of extensive tributaries including the El Gato and Alcarayón streams. In the north-west of the region the La Rocina, El Partido, and La Cañada water courses drain southwards into the marshland.

The Doñana area comprises three large ecosystems: stabilised sands or cotos, a sand dune spit running parallel to the coast-line, and the marshland. The contact between the dune sand and marshland areas constitutes a seepage limit in La Vera-Retuerta (Serrano et al. 2006), an ecologically important area which provides moisture to grass meadows and hydrophitic vegetation, and feeds small creeks especially during periods of heavy rainfall. Much of the study area is covered by pine, although at the beginning of the 20th century a large number of economically valuable eucalyptus trees were planted. These had a significant impact on groundwater levels because of their high water demand. From the mid-1990s eucalyptus started to be cut down, but approximately 6400 ha remain today.

2.2. Hydrogeology

The Almonte-Marismas aquifer system (Figure 1b) covers 2640 km^2 of the south western part of the lower Guadalquivir basin. It is composed of Miocene and Quaternary sediments: silt, sand, and gravel (Trick and Custodio 2004). The alluvial deposits of fine materials located in El Abalario are partially covered by aeolian sands, while in the central plain they are covered by estuary and marshland silt and clay containing some sand and gravel, with a total thickness of up to 100 m (Figure 1c). The depth of the aeolian sands varies from over 100 m at the coast to approximately 10 m at the northern edge of the region. Groundwater predominantly circulates from the north-east to the south and then east before discharging to the Atlantic Ocean or north into the La Rocina stream, the main permanent tributary to the marshland. The aquifer system of Almonte-Marismas drains into the Tinto River, along the coast, and into temporary pools and springs that drain into the marshland. Groundwater abstraction for irrigation amounts to 60–90 hm^3 year^{-1} (1 hm^3 = 10^6 m^3), causing decreases in the piezometric level and reductions in groundwater contributions to the streams supplying the marsh during the summer. Agriculture is concentrated in three areas: around El Rocío village, between the coast and the Tinto River, and across the north-east boundary of the marshes. In the first two of these areas strawberries and citrus fruits are the main crops, and groundwater is the principal source of water for irrigation. In the third area rice and cotton are the main crops, which are irrigated with both river water and intensively abstracted groundwater. Groundwater is also abstracted to supply the towns and the tourist resorts of Mazagón and Matalascañas (3–6 $hm^3 year^{-1}$), with an associated impact on the wetland.

The permeability of the main geomorphological units is very different: the aeolian sands correspond to an unconfined aquifer (with a shallow water table and several flow systems) while groundwater is confined below the silty-clay deposits of the floodplain. The relatively thick aeolian sand deposits, which are occasionally inter-layered with finer sediments, form a relatively low permeability, unconfined upper aquifer with a shallow water table. This overlies a thinner, and more heterogeneous, lower aquifer that becomes leaky-confined beneath the marshland silt and clay (Trick and Custodio 2004). The transmissivity of the lower aquifer is higher than that of the upper aquifer, due to the presence of layers containing coarse sand and gravel. The aquifer system is underlain by impermeable marine marls. The transmissivity of the aquifer increases from north to south, varying from on average 100 $m^2 d^{-1}$ around Almonte to 3000 $m^2 d^{-1}$ beneath the marshland (FAO 1975; Trick and Custodio 2004). In the unconfined aquifer effective porosity varies between 2 and 5 %. Confined storage coefficient values are in the range 10^{-3} to 10^{-4} (IGME 2009).

Most of the recharge is derived from rainfall over the unconfined aquifer, irrigation return flow, and by lateral inflow from the Aljarafe aquifer. Recharge, which is produced during spring and autumn predominantly, has been estimated to total 200 $hm^3 year^{-1}$ (IGME 1992) on average. The confined aquifer beneath the marshland is fed by lateral groundwater flow. Groundwater discharges from the aquifer through the rivers and streams, via lateral flow to the sea, evapotranspiration, leakage at the dune-marshland margin, and to a lesser extent via upflow through the silt and clay to the marshland. Groundwater abstraction for agricultural and industrial use and for public supply is also significant and has reversed the direction of groundwater flow in some areas, such as in the north-eastern part of the marshland (UPC 1999).

3. Methods

The methodology applied to quantify the potential effects of climate change on the Doñana wetland system is summarised in four stages:

1. Future time-series of catchment precipitation and temperature were calculated by perturbing historic time-series of these variables using monthly *change factors*. These change factors represent the difference between a GCM simulation of the reference climate, 1961–1990, and a future climate, which in this study is the period 2071–2100 under the A2 emissions scenario (IPCC 2000). Here we applied monthly change factors derived from 13 GCMs reported in the IPCC Fourth Assessment Report (IPCC 2007).
2. The 13 time-series of future precipitation and potential evaporation (calculated from the temperature) were used to drive a ZOODRM (Mansour and Hughes 2004) distributed groundwater recharge model of the area.
3. Each future recharge time-series was used as input for a calibrated MODFLOW (McDonald and Harbaugh 1988) groundwater flow model of the Almonte-Marismas aquifer. All of the other groundwater model parameters remained the same as the baseline run from 1975 to 1997.
4. Changes in state variables between the baseline and 13 future simulations were calculated.

3.1. Climate change scenario generation and downscaling

In this work the A2 greenhouse gas emissions scenario (IPCC 2000) was applied. This medium-high emissions scenario is based on a socio-economic storyline that supposes a world of independently operating, self reliant nations with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than in other storylines (IPCC 2000). The simulated climate based on this scenario was derived from the 13 GCMs listed in Table 1, which are reported in the Fourth Assessment Report of the IPCC (IPCC 2007).

GCMs do not accurately simulate local climate, but the internal consistency of these physically-based climate models means that they provide the current best estimate of the ratios and differences (scaling factors) of future precipitation and temperature from historical (base case) records. A number of different spatial and temporal downscaling techniques can be used to derive finer resolution climate information from coarser resolution GCM output, for example based on statistical methods (e.g., Wilby et al. 1998) such as stochastic weather generators (Kilsby et al. 2007), or dynamical downscaling using regional climate models (Graham et al. 2007). The simplest method for modifying time series of catchment model driving data using GCM outputs is the delta change or change factor (CF) method (Wilby and Harris 2006). For a given variable, the difference between the simulation by a GCM of a reference climate and a future climate are used to adjust sequences of catchment model driving variables. Whilst the CF approach offers a robust method to compare average outcomes from different climate models, it cannot provide any information on changes in hydrological extremes (Graham et al. 2007) because it assumes that the variability of the climate remains unchanged in the future. However, the CF method remains one of the most widely used for analysis of climate change impact on non-extreme variables and was used here to quantify changes in the monthly means of state variables. Change factors were used to perturb historic sequences of daily rainfall and monthly PE. The 2080s time horizon was selected because it has the strongest ratio between the signal of change and natural variability and the A2 emissions scenario (IPCC 2000) was applied because it is one of the most commonly considered scenarios. Simulated changes in mean monthly temperature and rainfall between the 1961–1990 and 2071–2100 periods for the A2 scenario were used. These factors were obtained for the 13 GCMs from the IPCC Data Distribution Center (http://www.ipcc-data.org/ar4/gcm_data.html). Because the middle of the baseline period for the catchment simulation (1975–1997) differs from that of the climate model baseline (1961–1990) by 10.5 years, the monthly change factors were adjusted to account for this. This has been done by linearly scaling the factors assuming that the rate of change of temperature and precipitation is constant over time. The resulting perturbed time-series of driving climate variables were applied to the ZOODRM distributed recharge model, which calculated recharge for the transient groundwater flow model of the Almonte-Marismas aquifer.

3.2. Recharge estimation

Groundwater recharge was calculated using the gridded ZOODRM model (Mansour and Hughes

2004). ZOODRM has been applied to a wide variety of hydrological regimes within temperate and semi-arid regions (Hughes et al. 2008; Jackson et al. 2011). The model uses a soil moisture balance approach based on the FAO method (FAO 1998) to calculate, evapotranspiration, surface runoff, and recharge using spatially distributed daily rainfall and potential evaporation time-series and land surface elevation, land-use, and geological data. A digital terrain model is used to route runoff across the land surface, which can subsequently infiltrate to form indirect recharge. The proportion of rainfall forming runoff is related to the topography, soil type, and geology.

Lerner et al. (1990) provided a method for determining if soil moisture budgeting methods are applicable to a given terrain. This requires that potential evaporation is less than 1.5 and 3 times the amount of precipitation plus irrigation during the wet and dry seasons, respectively. This criterion is not met during the dry season within the Doñana area but because very little recharge occurs during the summer months, due to the large disparity between PE and precipitation, the approach remains acceptable. Calculated recharge rates have been found to be comparable to those derived by Guardiola-Albert et al. (2005) who calculated mean recharge to be 0.2 mm d^{-1} using soil water balance methods and inverse groundwater modelling (UPC 1999).

The baseline period was simulated using a network of 22 rain gauges with daily time series. Rainfall was distributed in space by comparing the long-term average rainfall at a grid node with that at an associated rainfall station. Grid nodes were associated with a rainfall station by constructing Thiessen polygons around the rainfall gauges. The distribution of long-term average rainfall in space was constructed by kriging the point long-term average values at the rain gauges to produce a surface.

The temperature time-series for the 19 meteorological stations within the model area are very similar and therefore, a single temperature time-series was used to construct a record of potential evaporation. The Palacio de Doñana (Figure 1a) temperature record, which covers the period November 1978 to March 2007, was used to calculate PE. The Los Palacios y Villafranca station has a reference evaporation (ET_0) record, based on measured meteorological variables, from

October 2000 to July 2007. Using Palacio de Doñana temperature data over the same period, a PE time-series was constructed using the Blaney Criddle method (Allen and Pruitt 1986). Monthly Blaney Criddle k values were calibrated by fitting the calculated PE time-series to the measured ET_0 values. The comparison between the monthly mean measured ET_0 values and the calculated PE values is shown in Table 2. The daily consumptive use coefficient, k, which depends on the vegetation type and season, was interpolated from the monthly values to avoid the occurrence of step changes in PE between months. A time-series of PE was subsequently constructed for the full baseline period between January 1975 and December 1997 using the full Palacio Doñana temperature record. It was assumed that the period January 1975 to October 1978, for which there are no temperature data, is equivalent to the period from January 1983 to October 1986, which is characteristic of a non-extreme period of temperature variations.

The spatial distribution of vegetation was assumed to be constant during the baseline and future modelling periods and based on 15 zones derived from land-use data for 1999. In eight of these zones the FAO method for calculating recharge was applied and crop parameter values were based on those specified in the FAO guidelines (FAO 1998). Within the remaining seven zones there were insufficient data to implement the FAO method and therefore the Penman-Grindley (Penman 1948; Grindley 1967) soil moisture deficit method (SMD) was applied. The Root Constant, C, and Wilting Point, D, parameters used in the SMD method were based on values presented by Lerner et al. (1990) but were adjusted during the model calibration process. Run-off is routed across the land surface according to topographic elevation. The percentage of rainfall becoming run-off varies across the model, and was defined using zones. These zones were based on the hydraulic conductivity classification of the surface geology.

The ZOODRM model was calibrated by comparison against detailed groundwater balances obtained in previous studies (Guardiola-Albert et al. 2005). The spatially-distributed and temporally-varying recharge series calculated by the ZOODRM model for the baseline period and the 13 future climates formed input to the groundwater flow model of the Almonte-Marismas aquifer.

3.3. Almonte-Marismas groundwater flow model

The numerical groundwater flow model was constructed using the MODFLOW code (McDonald and Harbaugh 1988). The model grid covers an area of 2600 km^2 and was divided into two layers and a uniform horizontal mesh of 500 m square cells. The upper layer represents the thick sand deposits, occasionally inter-layered with finer sediments and the lower layer represents the heterogeneous sand and gravel lower aquifer. The base of this two-layer aquifer system coincides with the top of the underlying low permeability Miocene marls.

The limits of the model were defined along physically justifiable boundaries. In the south the Atlantic Ocean was represented by a series of constant head cells. In the north a constant flow boundary condition was specified along the edge of the outcrop of the marls, which coincides with a line of springs. In the north-east a constant flow boundary condition was specified representing groundwater flow from the Aljarafe aquifer, the rate of which was based on estimates of transmissivity from pumping test data and groundwater head gradients from levels in observation boreholes. Elsewhere the groundwater model boundaries were defined as no-flow, however, a number of head-dependent boundary conditions were also set within the model (Figure 2). In the east groundwater discharges to the Guadalquivir River through a series of MODFLOW *river cells*. River cells were also included in the model to simulate flows to the Tinto River in the north-west and the Gudiamar River in the north-east. *Drain cells* were used to model the marshland area and discharges to the associated ecotone (seepage limit), along the border with the dune sand aquifer, and to coastal springs in the south. The network of intermittently flowing watercourses within the study area was modelled using MODFLOW *stream cells* (Prudic et al. 2004). Groundwater abstractions for irrigation and water supply were included in the model, the location and pumping rates of which were based on monitored data. This totals on average approximately 47 $hm^3 year^{-1}$.

The hydraulic parameters of hydrogeological zones within the model, based on the geology (Figure 1b), were specified initially using data from more than 400 pumping tests but adjusted during the calibration of the model against observed groundwater heads (Guardiola-Albert et al. 2005). Model hydraulic conductivity values range from 0.001 to 50 m day^{-1}. Initially a steady-state model was calibrated to historic mean groundwater levels in over 300 boreholes. Subsequently a time-variant model of the period 1975-1997 was developed. Simulated groundwater level time-series were compared to data from more than 1000 observation boreholes in the study area. The comparison between the simulated and observed groundwater levels at four of these boreholes is shown in Figure 3. A decrease in groundwater levels caused by the introduction of intensive irrigation is clearly identifiable within the marshland area (borehole 4).

The following error measures were used to evaluate the goodness of fit of the calibration of the model: mean error (ME), mean absolute error (MAE), and standard root mean square error (SRMSE). Anderson and Woessner (1992) consider that an acceptable fit to the observed data is achieved when the ME and SRMSE values are less than 0.5 m and 10%, respectively. These head error measures for the numerical model of the Almonte-Marismas aquifer are listed in Table 3. These values indicated that the calibration was more than acceptable. Another indicative parameter of the acceptability of the simulation was the mass balance error, which was considered to be admissible when its value is around 1% of the total inflow (De Marsily 1986). The maximum values of the absolute differences between the inputs and outputs obtained in the steady-state and transient simulations were 0.02 and 0.15%, respectively.

3.4. Groundwater simulations with GCM projected climate

Each of the future recharge series, calculated by the ZOODRM code using the climate output from the 13 GCMs, were input into the groundwater flow model. All other model stimuli and parameters remained the same as the baseline (1975-1997) run. Consequently, it was assumed that changes in groundwater abstraction and management practice do not change between the baseline period and the 2080s. The transient groundwater model simulates fluctuations in groundwater level, and groundwater discharge to the rivers, marshland, and sea. The comparison between the baseline simulation and the future simulations was made by calculating differences in recharge, groundwater levels, and the components of the flow balance.

4. Results

4.1. Projected climatology and impacts on groundwater recharge

Temperature and potential evaporation

Figure 4 shows the projected increase in mean monthly temperature from the baseline period (Table 2) for each of the 13 GCMs. All of the GCMs project a warming of at least 1.2°C for each month for the Doñana area. Between the months of November and March the increase, described by the average of the ensemble of models (black line in Figure 4), varies between 2.4 and 3.5°C. Between the months of April and October this ensemble average increase ranges from 4.2 to 4.7°C. Projected temperature increases are much higher during the summer, reaching a maximum value of 7.4°C for the HADCM3 model projection. The CSMK3 model projects the smallest increase in temperature of between 1.0°C in February and 2.3°C in September.

The calculated increases in monthly average PE for the 2080s from the baseline period are shown Figure 4. Percentage increases in PE are highest between the months of May to October with ensemble average values of between 11.2 and 13%. The CSMK3 model projects the smallest monthly increases in PE for the Doñana area of between 4.0 and 6.5%. The HADCM3 model projects the greatest monthly increases of PE between 10.0 and 20.8%.

Precipitation

Figure 4 shows the projected changes in mean monthly precipitation for the 2080s from the baseline period (Table 2) for each of the GCMs. Negative values represent a decrease in precipitation and vice versa. The monthly averages of the ensemble change factors suggest a decrease in precipitation throughout the whole year with a maximum decrease of 0.51 mm d^{-1} in November. Uncertainty in the projection of the change in rainfall is greatest in winter with some GCMs projecting an increase in rainfall and some a decrease. As would be expected, reductions are generally projected to be less in summer when rainfall rates are low.

A number of GCMs project significant changes in precipitation during the winter. For example, the IPCM4 model projects an increase of 0.4 mm d^{-1} in the months of February and March, HADCM3 an increase of 0.4 mm d^{-1} in December, and CNCM3 an increase of 0.35 mm d^{-1} in September. A decrease of 1.3 mm d^{-1} is projected by the GFCM20 model in February and April and CNCM3 projects a decrease of 1.2 mm d^{-1} in November. All models project changes between -0.11 and +0.09 mm d^{-1} in August.

Recharge

Figure 5 shows the monthly mean values of recharge for all the 13 future simulations and the entire modelled area, as well as the average of the ensemble and the historic mean, simulated using ZOODRM. Mean monthly recharge during the baseline period varies from 0.93 mm d^{-1} in February to none in July and August. Decreases in mean monthly recharge are produced for at least nine months of the year in all 13 future simulations. Six of the 13 future simulations produce reductions in mean monthly recharge over the whole year. The most pronounced decrease, of 0.57 mm, is simulated in December using the GFCM20 climate projection. For all models the largest reduction in recharge, as a percentage, occurs in April. Bootstrapped 95% confidence intervals on the ensemble mean of the percentage changes in mean November recharge are -44 and -23%. For mean December recharge, these confidence intervals are -44 and -24%.

Annual recharge, expressed by the average of the ensemble of the 13 future simulations, is simulated to decrease by 35%. However the spread of the simulations ranges from a 57% decrease using the CNCM3 projection to a 14% decrease using the HADCM3 and NCPCM projections. Bootstrapped 95% confidence intervals on the ensemble mean of the percentage changes in mean annual recharge are -43 and -27%. These values are similar to that estimated by Custodio et al. (2007) in Doñana area, that suggest a decrease of recharge of 50% for an increase of temperature of 1ºC.

4.2. Climate change impacts on groundwater levels

Figure 6 depicts differences in groundwater levels across the aquifer for December 2084 relative to the December 1979 in the baseline period. This date was selected as the monthly rainfall is close to the average rainfall in the area and also because it follows a period which was not very dry or wet. The differences in groundwater level across the aquifer range between -17 and +2 m at this time.

Absolute differences in groundwater level between the baseline and future simulations across the northern part of the Almonte-Marismas aquifer and over some areas of the marshland are less 0.5 m (see white areas in Figure 6). The largest reductions in groundwater level, of up to 17 m, are simulated across the unconfined groundwater mound in the El Abalario region. Other areas where there are significant simulated declines in the water table include the upper catchment of La Rocina stream (-1 to -5 m) and the irrigated Los Hatos region (-1 to -3 m). There is not a zone in which there is a significant rise of water levels in any of the simulations. The GFCM21 simulation produces the greatest decreases in water levels in comparison with the baseline simulation, with declines of up to 17 m. The NCPCM simulation is most similar to the baseline with decreases of up to 5 m in El Abalario. In general, for the 13 future simulations, water levels under the marshland tend to decrease between 0 and 6 m, but this fact has to be considered along with the reduction in discharge from the aquifer to the streams that flow into the marshland. In the irrigated Los Hatos area the maximum decline in groundwater level is 4 m under the GFCM21 simulation.

The simulations show that there is an impact on changes to hydraulic head in terms of the overall water table configuration. Changes in groundwater level increase significantly away from the coast to the north (Figure 6). Some areas of the marshland are less affected by the change in climate. However, there are notable differences in the groundwater table configuration between the future simulations and the baseline, accounting for the redistribution of water within the system.

4.3. Preservation of groundwater ecological discharges

Groundwater discharge to streams feeding the marshland

For each future simulation temporal changes in the water balance have been calculated to examine the exchange of water between the aquifer and the main streams and drains that maintain the marshland: Guadiamar, Marismas, El Partido and La Rocina (Table 4). Whilst on average, flows from the streams to the aquifer do not change significantly with respect baseline values, groundwater contributions to stream flows in the Marismas and La Rocina basins are considerably diminished by on average 53% and 36%, respectively. The discharge from the aquifer to the Guadiamar and El Partido basins, again as represented by the ensemble average, decreases by 7% and 15%, respectively, compared to the baseline values. Similar behaviour was also described in the preliminary study of Guardiola-Albert et al. (2009) in which climate change impacts were shown to have a more significant effect on groundwater outflows to rivers than river flows returns to the aquifer. This can be explained by the fact that during dry periods the streams are disconnected from the aquifer. During dry periods groundwater recharge and storage are reduced resulting in water table declines. As a result baseflow is reduced, and when the water table lies below the streambed there is a disconnection between the stream and the aquifer.

All the 13 models simulate lower values than the historic rates throughout the year and a dampening of the seasonal pattern of flows to the marshland. The most severe reduction in flow to the marshland of 26.7 hm^3/y is simulated using the outputs from CSMK3. These large reductions in groundwater discharge to the marshland, combined with the predicted decreases in baseflow in the La Rocina stream baseflow, represent a major decrease of water supply to the Doñana ecosystem. Similar impacts have been reported for other southern Spanish wetlands (Rodríguez-Rodríguez et al. 2006).

Groundwater discharge to the sea

To evaluate the outputs to the sea, simulated flows flow from the springs associated with cliffs on the coast and flows to the constant head boundary are combined. The resulting changes in monthly average discharges to the sea are shown in Figure 7. The simulations indicate a decrease of coastal groundwater discharge throughout the whole year, with an ensemble mean decrease of 35%. Some future simulations however (e.g., GFCM21) suggest decreases of more than 50%. Although not assessed here, such changes would result in enhanced saline intrusion and deteriorations in groundwater quality.

5. Discussion

In general, the results of this modelling study indicate that the change in climate by the 2080s, will lead to a reduction in groundwater resources. Mean annual recharge rates are simulated to decrease by between 14 and 57% using the different GCM projections. The average of the ensemble of future simulations suggests that monthly recharge will decrease throughout the year. These decreases in recharge result in significant reductions in groundwater heads and changes in the water table configuration. Decreases in groundwater level depend on the simulation and the location but can be as much as 17 m over the unconfined interfluve regions. Whilst the future simulations suggest a change in the seasonal distribution of recharge to the aquifer, this does not translate into a significant change in the distribution of mean monthly groundwater levels. This seems to indicate that climate change will lead to a monotonic decrease of groundwater levels rather than a significant impact on seasonal fluctuations of groundwater levels. However, this result must be considered in the context of the use of the change factor approach in this study which only perturbs the monthly means of the driving climate variables and not the variability of the future climate.

Such declines in groundwater level result in a reduction of groundwater flow into the streams and to the marshland and an obvious reduction in the availability of water required to maintain aquatic life in the wetland and riparian ecosystems, especially in summer (Trick and Custodio 2004; Custodio et al. 2007). All 13 future simulations indicate decreases in discharge, of up to 68%, from the aquifer to the La Rocina and Marismas basins, which form the main water supplies to the marshland during the summer and which sustain important ecological systems. The consequences of these baseflow reductions, together with the decrease of direct discharge from aquifer to marshlands, could be drastic as it would reduce the availability of water that is necessary for the maintenance of aquatic life in the wetland and riparian ecosystems, especially during summer (Serrano et al. 2006). In addition, for the La Rocina stream, the amount of water flow has approximately halved within the last 20 years as a consequence of strawberry farm encroachment and the associated interception of groundwater. Hence, as discussed by Primack (2000) and WWF España (2006) climate change is another factor limiting the width of the riparian corridor along the stream, and its effect must be considered within management plans developed by the water resource regulators and stakeholders. As suggested by Custodio et al. (1994), predicted decreases in discharge rates from the aquifer to the sea, of more than 50% by some models, would also result in the advance of saline water inland.

To put the potential effects of climate change on the Doñana wetland into context, a comparison has been made between the simulated impacts and current groundwater abstraction rates within the region. Simulated minimum, ensemble average and maximum decreases in total groundwater discharge (MODFLOW stream cell plus drain cell leakage) to the La Rocina, El Partido and Las Marismas basins are presented (Table 4). Groundwater abstraction in each of these catchments, for both irrigation and public supply, is also given. Mean historic total groundwater abstraction rates in the La Rocina, El Partido, Las Marismas and Guadiamar basins are 8.0, 0.3, 18.6, and 0.1 hm^3/year, respectively. These are equivalent to 24, 3, 47, and 1% of the historic groundwater discharge to each catchment, respectively. Decreases in groundwater discharge to the basins due to climate change are significantly greater than historic rates of abstraction in both the La Rocina and Las Marismas basins. In the El Partido basin one of the future simulations produces a 4% increase in mean groundwater discharge but the worst case simulation produces a 73% reduction in groundwater discharge. The ensemble averages of the 13 future simulations represent decreases in groundwater discharge to these four basins of between 7 and 53% of mean historic discharge rates. These values provide the following useful guidelines to water and wetland policy-makers and stakeholders: (i) simulated climate induced decreases in groundwater discharge to the surface are substantive in comparison to the current wetland groundwater balance, (ii) these decreases are proportionally greater in the La Rocina and Las Marismas basin, than in the El Partido and Guadiamar basins, (iii) modelled reductions in groundwater flow to the surface associated with climate change are greater than current groundwater abstraction rates in most of the future simulations, and (iv) in the larger La Rocina and Las Marismas catchments, however, simulated worst case decreases in groundwater discharge to the surface are 2.4 and 1.5 times greater than current abstraction rates, respectively.

This work has neglected possible changes in land-use, groundwater abstraction, and water resource management that may occur in response to a need to adapt to the changing climate and the results must be considered in the context. It is necessary to underline that all investigations for this study were realised on a regional scale and thus conclusions drawn also have to be regarded in this context. Nevertheless, it seems realistic to claim that climate change is likely to have a dramatic impact on groundwater resources, due to the combined effect of direct and indirect factors. Despite all efforts to mitigate climate change, there will be a need to implement significant adaptation measures to minimise the effect of climate change on groundwater resources (WWF España 2006).

The analyses presented here focus on the direct impact of climate change on groundwater resources, which have been simulated to be potentially large. The results have shown that GCM uncertainty is significant in the assessment of the potential impacts of climate change on this internationally important wetland. However, the direction of the change is consistent across all 13 of the future simulations. The spread of the change in mean recharge for the 2080s time-slice is bounded by simulated decreases of 14 and 57%. Furthermore, bootstrapped 95% confidence intervals on the average of this ensemble of simulated changes in mean recharge are -43 and -27%. Therefore, the results suggest that a significant change in the hydrological regime will occur over the coming century. Importantly, this result has been placed within the context of the current exploitation of the groundwater resource. Decreases in groundwater discharge to the surface water basins supplying the marshland have been simulated to be greater than current groundwater abstraction rates in the large majority of the future simulations. Consequently, even if the use of groundwater for public supply and irrigation is stopped, the supply of groundwater to the wetland is likely to diminish. Further studies are required to put the impact of climate change on groundwater resources within the context of human exploitation of groundwater resources.

Whilst these findings neglect other human induced effects such as changes in water use, groundwater abstraction, and land-use and soil degradation, the methodology provides a practical and useful way to generate a physically based evaluation of the impacts of climate change on a groundwater system. As suggested by Kuhn et al. (2011) to provide a more complete understanding of the impact of climate change on wetland systems it will be necessary to consider indirect effects, such as changes in land use, irrigation, and groundwater exploitation. To improve the assessment of the impacts on this wetland of great ecological importance there is an urgent need to develop a complete water balance model based on a fully coupled surface water-groundwater model.

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Tables

Model	IPCC-DDC Acronym	Modelling Group	Country	Spatial Resolution Mesh (Long x Lat)
CNRM-CM3	CNCM3	Météo-France / Centre National de Recherches Météorologiques	France	Gaussian 128 x 64
CSIRO-Mk3.0	CSMK3	CSIRO Atmospheric Research	Australia	Gaussian 192 x 96
ECHO-G	ECHOG	Meteorological Institute of the University of Bonn, KMA meteorological inst., and M & D group	Germany / Korea	Gaussian 96 x 48
GFDL-CM2.0	GFCM20	Geophysical Fluid Dynamics Laboratory	USA	Regular 144 x 90
GFDL-CM2.1	GFCM21	Geophysical Fluid Dynamics Laboratory	USA	Regular 144 x 90
GISS-ER	GIER	NASA / Goddard Institute for Space Studies	USA	Regular 72 x 46
UKMO-HADCM3	HADCM3	UK Met Office	UK	Regular 96 x 73
INM-CM3.0	INCM3	Institute for Numerical Mathematics	Russia	Regular 72 x 45
IPSL-CM4	IPCM4	Institut Pierre Simon Laplace	France	Regular 96 x 72
MIROC3.2 (medres)	MIMR	National Institute for Environmental Studies, and Frontier Research Centre for Global Change	Japan	Gaussian 128 x 64
ECHAM5/ MPI-OM	MPEH5	Max Planck Institute for Meteorology	Germany	Gaussian 192 x 96
CCSM3	NCCCSM	National Centre for Atmospheric Research	USA	Gaussian 256 x 128
PCM	NCPCM	National Centre for Atmospheric Research	USA	Gaussian 128 x 64

Table 1 GCMs considered in this study. More details at http://www-pcmdi.llnl.gov

Month	1	2	3	4	5	6	7	8	9	10	11	12
Los Palacios y Villafranca ET_0 (mm day^{-1})	1.4	2	2.9	4.2	5.3	6.2	6.4	5.7	4.3	2.7	1.7	1.2
Blaney Criddle ET_0 (mm day^{-1})	1.4	2.1	2.9	4.3	5.3	6.1	6.2	5.6	4.2	2.6	1.7	1.3
Los Palacios y Villafranca temperature (ºC)	10.2	11.5	13.9	15.2	18.1	21.2	23.9	23.5	21.7	18.4	13.9	11.2
Precipitation San Lucar de Barrameda (mm day^{-1})	2.48	2.45	0.98	1.22	1	0.3	0.03	0.09	0.66	1.81	2.86	3.45

Table 2 Monthly mean values of (i) measured reference evaporation ET_0 (mm day^{-1}) at Los Palacios y Villafranca meteorological station for the period October 2000 to March 2007, (ii) calculated reference evaporation ET_0 (mm day^{-1}) using the Blaney Criddle method, (iii) temperature (°C) at Los Palacios y Villafranca meteorological station for the period November 1978 to March 2007, and (iv) precipitation at Sanlucar Barrameda 'INM' meteorological station for the period 1975 to 1997

Simulation	ME (m)	MAE (m)	SRMSE (%)
Steady-state	0.23	4.45	4.05
1975-1997	-0.04	3.33	2.88

Table 3 Head error measures: mean error (ME), mean absolute error (MAE) and standard root mean square error (SRMSE).

		La Rocina basin	El Partido basin	Las Marismas basin	Guadiamar basin
Mean historic (1975-1997) groundwater discharge to basin		33.8	11.3	39.4	8.4
Mean historic groundwater abstraction for irrigation		7.8	0.3	18.2	0.1
Mean historic groundwater abstraction for public supply		0.2	0	0.4	0
Simulated change in groundwater discharge to basin due to climate change	Maximum	-18.7	-8.3	-26.7	-1.8
	Ensemble average	-12.2	-1.7	-20.7	-0.6
	Minimum	-8.4	+0.4	-16.9	+0.4

Table 4. Comparison of historic groundwater abstraction and simulated decreases in groundwater discharge to stream basins under future climate (hm^3/year)

Figures

Fig. 1 (a) Location of Almonte-Marismas aquifer. (b) Surface geology. (c) Two schematic geological cross-sections based on IGME (1992) and Custodio et al. (2009)

Fig. 2 Groundwater model structure and boundary conditions

Fig. 3 Observed and simulated groundwater levels at selected observation boreholes

Fig. 4 Projected changes in precipitation, temperature and PE for the 2080s under the A2 emissions scenario for the GCMs listed in Table 1

Fig. 5 Simulated monthly mean recharge for the baseline (1975–1997) and 2080s time-slices under the A2 emissions scenario

Fig. 6 Differences in groundwater levels across the aquifer for December 2084 relative to the December 1979 in the baseline period. Values were reclassified to range from 2 to -17 m

Fig. 7 Simulated monthly mean flows to the sea for the baseline (1975–1997) and 2080s time-slices under the A2 emissions scenario

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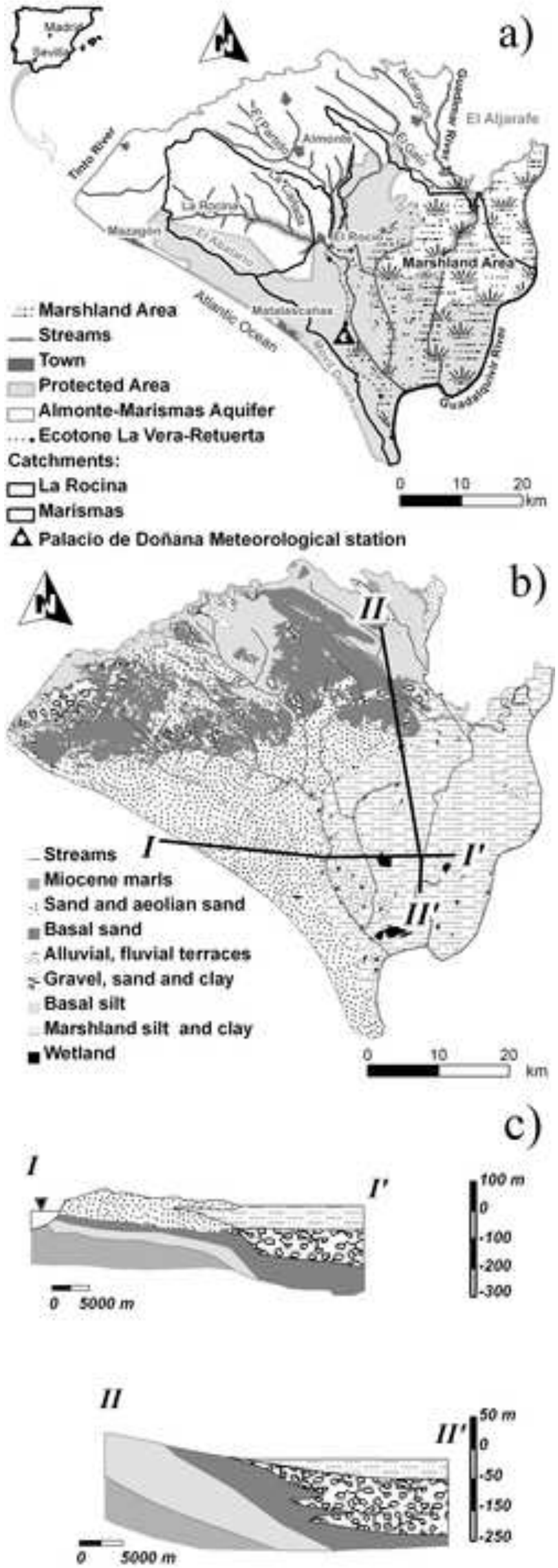

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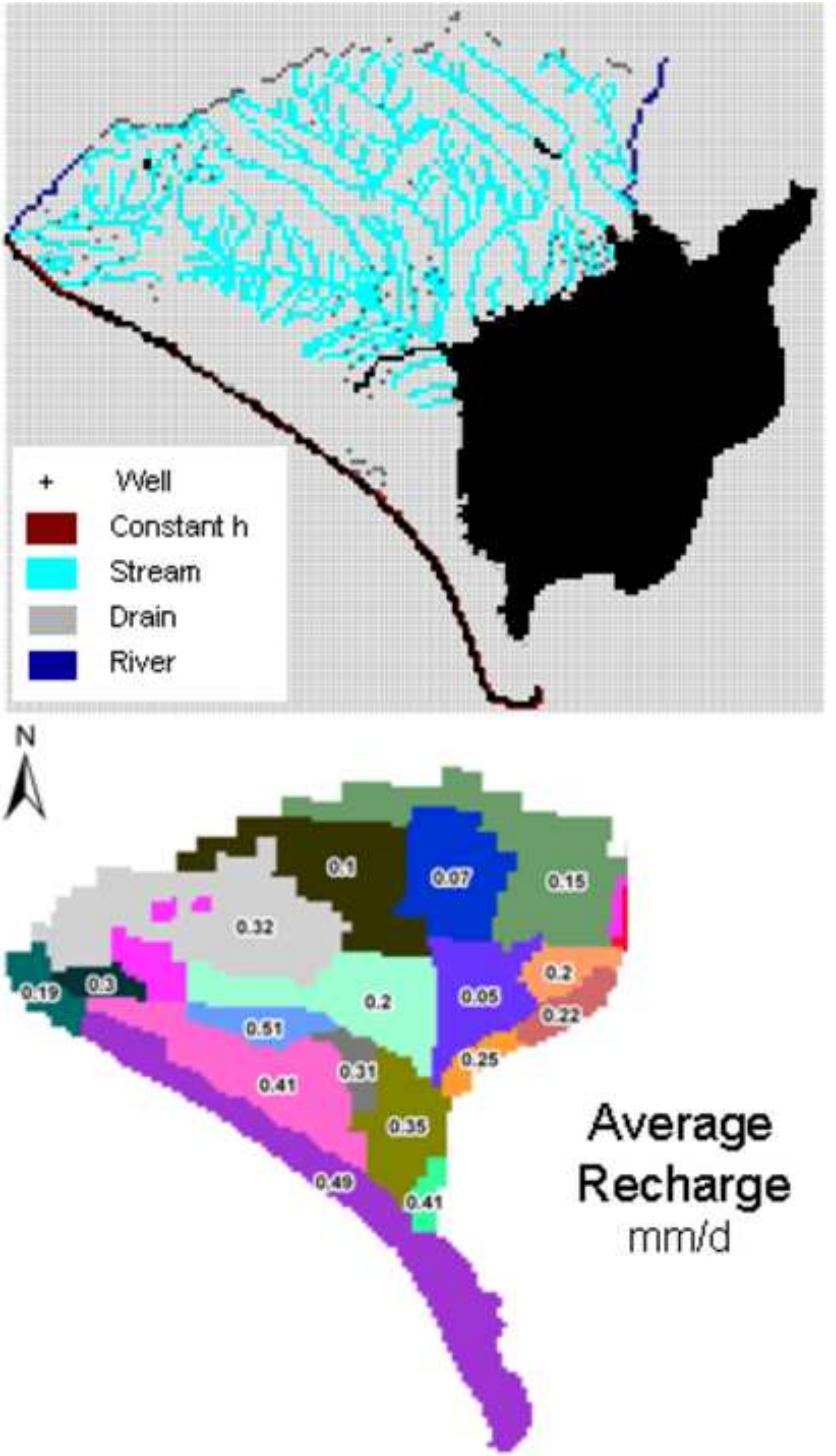

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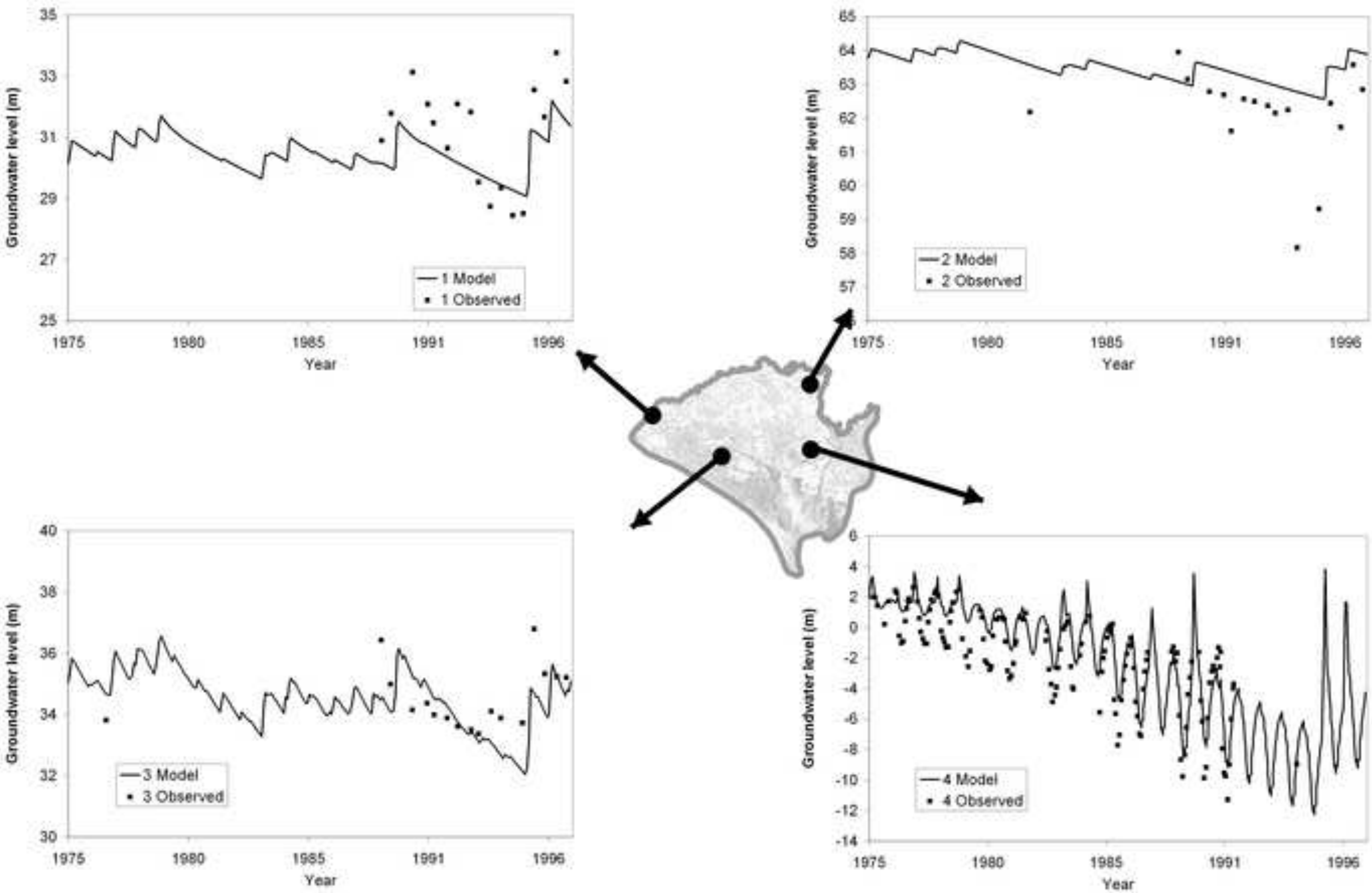

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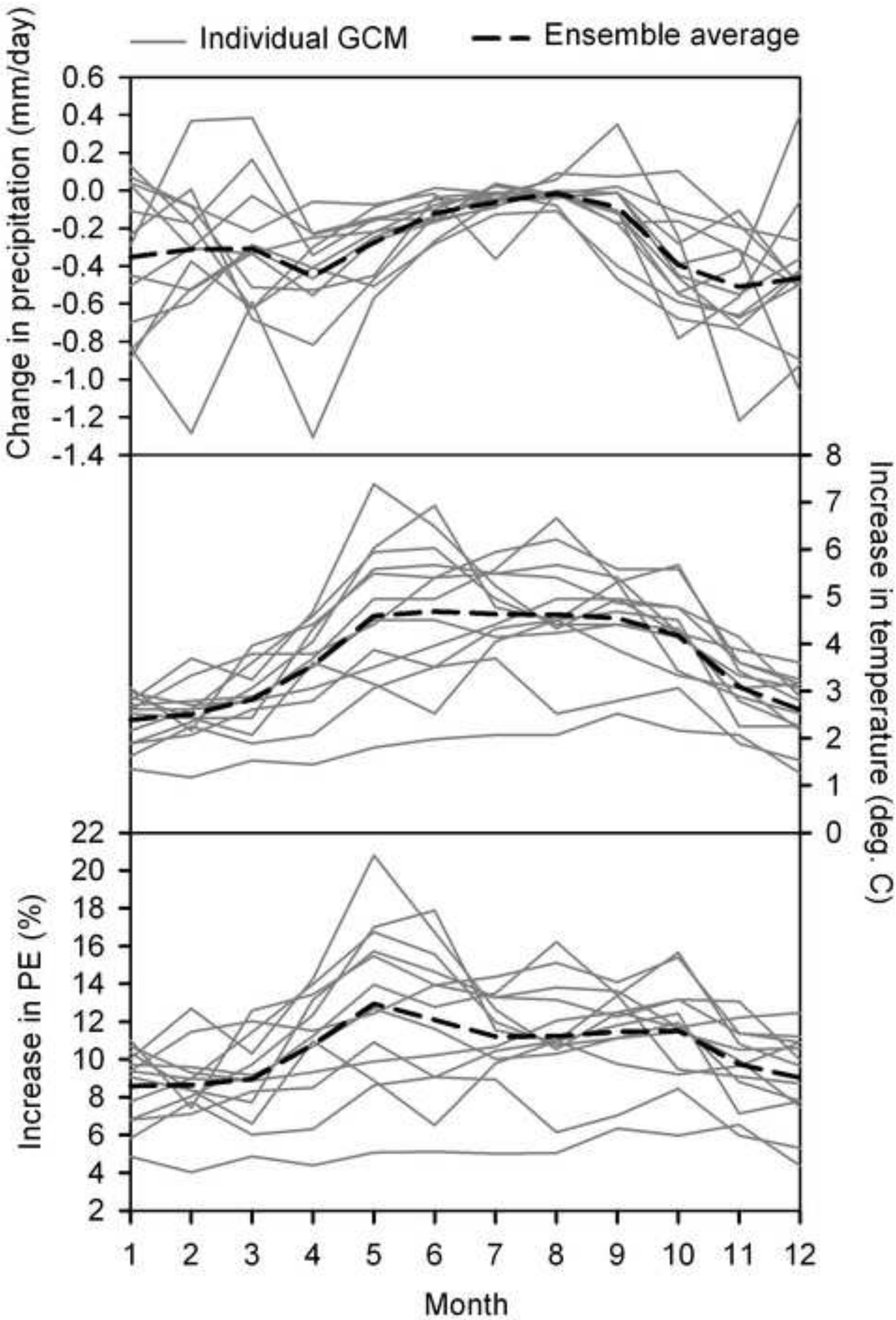

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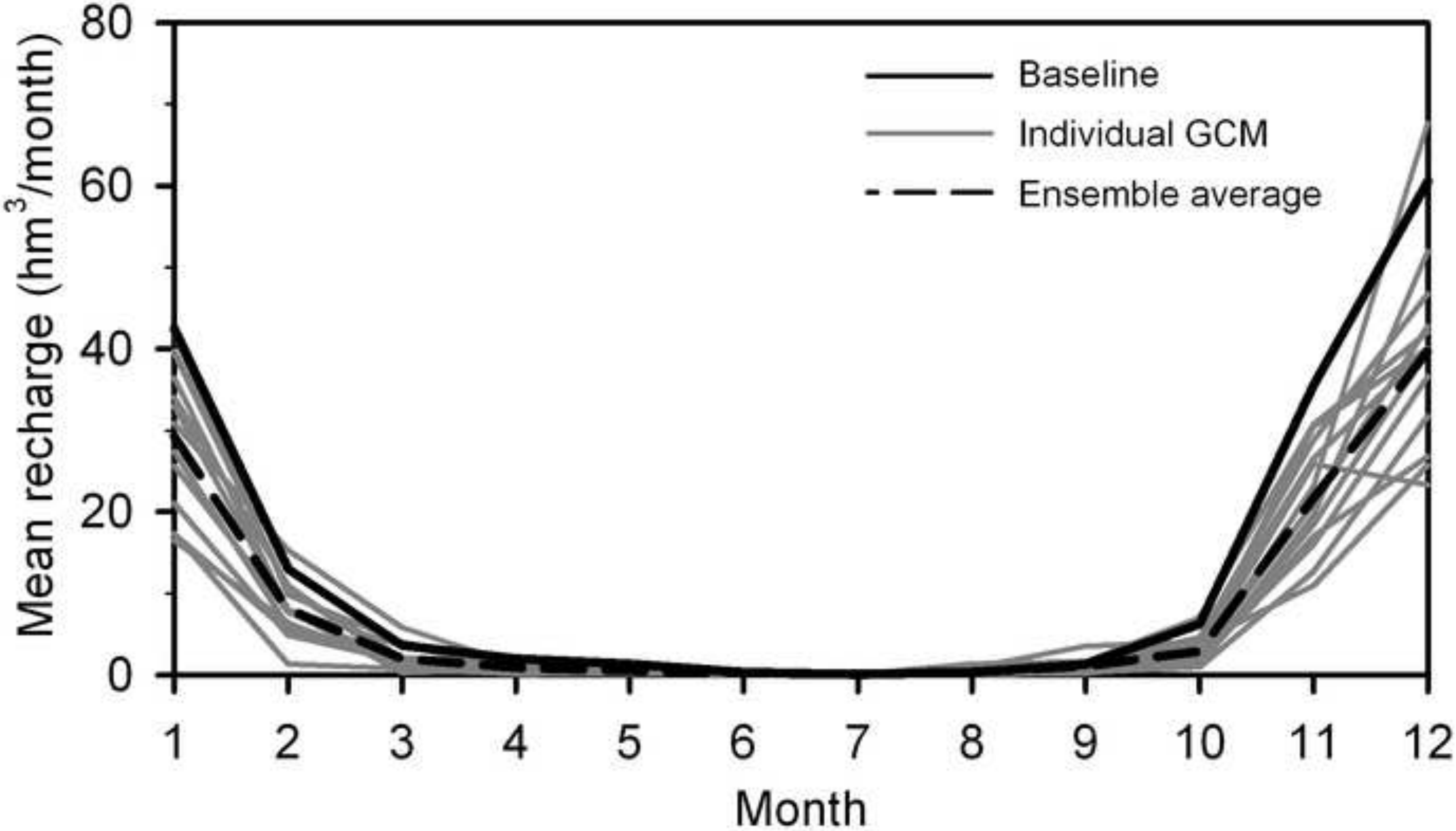

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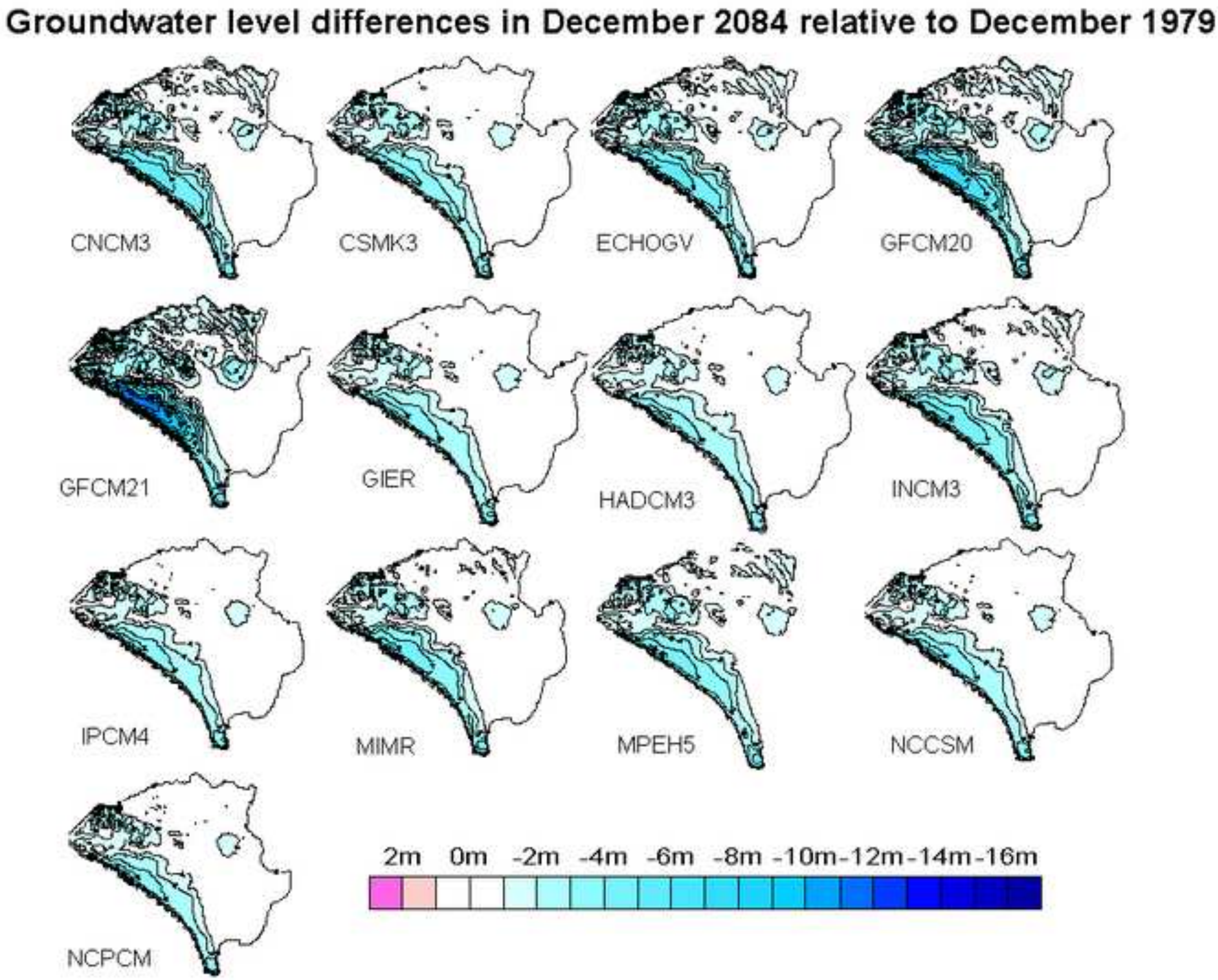

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