

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

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## 8 **Keywords**

9 Anthropogenic effect, Groundwater/Surface water interactions, Modelling, Recharge

## 10 **Abstract**

11 Climate change impacts on natural recharge and groundwater-wetland dynamics were investigated  
12 for the Almonte-Marismas aquifer, Spain, which supports the internationally important Doñana  
13 wetland. Simulations were carried out using outputs from 13 global climate models to assess the  
14 impacts of climate change. Reductions in flow from the aquifer to streams and springs flooding the  
15 wetland, induced by changes in recharge according to different climate projections, were modelled.  
16 The results project that the change in climate by the 2080s, under a medium-high greenhouse gas  
17 emissions scenario, leads to a reduction in groundwater resources. The reduction in mean recharge  
18 ranges from 14% to 57%. The simulations show that there is an impact on hydraulic head in terms  
19 of the overall water table configuration with decreases in groundwater level ranging from 0 to 17 m.  
20 Most simulations produce lower discharge rates from the aquifer to stream basins, with significant  
21 reductions in the larger La Rocina (between -55% and -25%) and Marismas (between -68% and -  
22 43%) catchments. Water flows from these two basins are critical to maintain aquatic life in the  
23 wetland and riparian ecosystems. Modelled climate-induced reductions in total groundwater  
24 discharge to the surface are generally larger than current groundwater abstraction rates. The results  
25 highlight that effective strategies for groundwater resources management in response to future  
26 climate change are imperative.

27 **1. Introduction**

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

40 In relation to water resources it is expected that climate change will result in increasing  
41 evaporation, more intense periods of precipitation, and more extreme hydrological events such as  
42 floods and droughts (IPCC 2007). Global climate models (GCMs) project mean annual increases in  
43 temperature of between 1.2 and 7.4°C in the Doñana area for the 2071–2100 time-slice (IPCC  
44 2007). Projections of changes in precipitation are less well constrained and the GCM outputs  
45 indicate that there is uncertainty about the sign of the change.

46 Over the last decade, an extensive amount of research has been published on how climate  
47 change might affect different aspects of the hydrological cycle, as reviewed by Bates et al. (2008),  
48 and impacts on groundwater resources are receiving greater attention (Dragoni and Sukhija 2008).  
49 Most of the research examining groundwater-related climate effects has used physically-based or  
50 empirical models to simulate groundwater system response to a change in climate. Whichever  
51 approach is adopted, it is necessary to quantify the change in precipitation and temperature under  
52 future conditions. This can be done by constructing plausible scenarios that are informed by the

53 range of regional climate model (RCM) and GCM outputs (e.g., Woldeamlak et al. 2007) or by  
54 downscaling individual GCM outputs to the catchment scale (e.g., Segui et al. 2010). Few studies of  
55 the effects of climate change on groundwater have used ensembles of more than three different  
56 scenarios in their assessment (Eckhardt and Ulbrich 2003; Woldeamlak et al. 2007; Goderniaux et  
57 al. 2009; Jackson et al. 2011).

58         Relatively few studies have examined the effects of climate change on groundwater resources  
59 in Spain. Manzano et al. (1998) estimated decreases in recharge of up to 16% for Mallorca for the  
60 period 1992–2040 compared to 1974–1988. Younger et al. (2002) simulated decreases in mean  
61 recharge of up to 8% and 16% for aquifers in Cataluña and Mallorca, respectively, by 2036–2045  
62 relative to pre-1995 values. Custodio et al. (2007) performed a preliminary analysis to quantify the  
63 effects of climate change on the Doñana area from empirical formulas of evapotranspiration. More  
64 recently, Aguilera and Murillo (2009) examined twentieth century recharge rates and identified  
65 decreasing trends in decadal mean recharge for four karstic aquifers in Alicante. Candela et al.  
66 (2009) applied two different climatic scenarios developed by the Intergovernmental Panel on  
67 Climate Change (IPCC 2000) to examine the effects of climate change and management scenarios  
68 on the Inca-Sa Pobla coastal aquifer, Mallorca and its associated wetland. GCM outputs were used  
69 to quantify recharge and drive a numerical model of the aquifer, for which overall decreases in  
70 natural recharge ranging from 4% to 21% by 2025 were simulated. In Doñana, Guardiola-Albert et  
71 al. (2009) investigated how groundwater outputs vary depending on the occurrence of dry, medium,  
72 or wet years.

73         Considering climate change pressures, and the importance of managing water resources  
74 effectively for ecosystem services within the Doñana area, this paper addresses the issue of GCM  
75 uncertainty in an evaluation of the impact of climate change on groundwater resources. First, we  
76 examine the potential impacts on groundwater recharge in the Almonte-Marismas aquifer. Second,  
77 we analyse the impact of a change in climate of southern Spain on the hydrogeological system, in  
78 particular on the groundwater discharge into the streams flowing into the marshland. The study used

79 outputs from 13 GCMs (Table 1) available from the IPCC Data Distribution Centre for the 2080s  
80 under the A2 emission scenario (IPCC 2000) to generate future downscaled sequences of  
81 precipitation and potential evaporation (PE) by perturbing historic sequences of these variables.  
82 This provides an indication of the level of confidence to be attached to the results of the impact  
83 assessment. These projected climatic variables were used to drive distributed recharge and  
84 groundwater flow models and calculate changes in rainfall recharge, groundwater levels in the  
85 aquifer and in groundwater discharge into the streams flowing into the marshland.

## 86 **2. Study area**

### 87 **2.1. Location and physiography**

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

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

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

105 southwards into the marshland.

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

## 115 **2.2. Hydrogeology**

116 The Almonte-Marismas aquifer system (Figure 1b) covers 2640 km<sup>2</sup> of the south western part of the  
117 lower Guadalquivir basin. It is composed of Miocene and Quaternary sediments: silt, sand, and  
118 gravel (Trick and Custodio 2004). The alluvial deposits of fine materials located in El Abalarío are  
119 partially covered by aeolian sands, while in the central plain they are covered by estuary and  
120 marshland silt and clay containing some sand and gravel, with a total thickness of up to 100 m  
121 (Figure 1c). The depth of the aeolian sands varies from over 100 m at the coast to approximately  
122 10 m at the northern edge of the region. Groundwater predominantly circulates from the north-east  
123 to the south and then east before discharging to the Atlantic Ocean or north into the La Rocina  
124 stream, the main permanent tributary to the marshland. The aquifer system of Almonte-Marismas  
125 drains into the Tinto River, along the coast, and into temporary pools and springs that drain into the  
126 marshland. Groundwater abstraction for irrigation amounts to 60–90 hm<sup>3</sup> year<sup>-1</sup> (1 hm<sup>3</sup> = 10<sup>6</sup> m<sup>3</sup>),  
127 causing decreases in the piezometric level and reductions in groundwater contributions to the  
128 streams supplying the marsh during the summer. Agriculture is concentrated in three areas: around  
129 El Rocío village, between the coast and the Tinto River, and across the north-east boundary of the  
130 marshes. In the first two of these areas strawberries and citrus fruits are the main crops, and

131 groundwater is the principal source of water for irrigation. In the third area rice and cotton are the  
132 main crops, which are irrigated with both river water and intensively abstracted groundwater.  
133 Groundwater is also abstracted to supply the towns and the tourist resorts of Mazagón and  
134 Matalascañas ( $3\text{--}6\text{ hm}^3\text{year}^{-1}$ ), with an associated impact on the wetland.

135 The permeability of the main geomorphological units is very different: the aeolian sands  
136 correspond to an unconfined aquifer (with a shallow water table and several flow systems) while  
137 groundwater is confined below the silty-clay deposits of the floodplain. The relatively thick aeolian  
138 sand deposits, which are occasionally inter-layered with finer sediments, form a relatively low  
139 permeability, unconfined upper aquifer with a shallow water table. This overlies a thinner, and more  
140 heterogeneous, lower aquifer that becomes leaky-confined beneath the marshland silt and clay  
141 (Trick and Custodio 2004). The transmissivity of the lower aquifer is higher than that of the upper  
142 aquifer, due to the presence of layers containing coarse sand and gravel. The aquifer system is  
143 underlain by impermeable marine marls. The transmissivity of the aquifer increases from north to  
144 south, varying from on average  $100\text{ m}^2\text{d}^{-1}$  around Almonte to  $3000\text{ m}^2\text{d}^{-1}$  beneath the marshland  
145 (FAO 1975; Trick and Custodio 2004). In the unconfined aquifer effective porosity varies between  
146 2 and 5 %. Confined storage coefficient values are in the range  $10^{-3}$  to  $10^{-4}$  (IGME 2009).

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

### 156 **3. Methods**

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

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

### 172 **3.1. Climate change scenario generation and downscaling**

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

179 GCMs do not accurately simulate local climate, but the internal consistency of these  
180 physically-based climate models means that they provide the current best estimate of the ratios and  
181 differences (scaling factors) of future precipitation and temperature from historical (base case)  
182 records. A number of different spatial and temporal downscaling techniques can be used to derive

183 finer resolution climate information from coarser resolution GCM output, for example based on  
184 statistical methods (e.g., Wilby et al. 1998) such as stochastic weather generators (Kilsby et al.  
185 2007), or dynamical downscaling using regional climate models (Graham et al. 2007). The simplest  
186 method for modifying time series of catchment model driving data using GCM outputs is the delta  
187 change or change factor (CF) method (Wilby and Harris 2006). For a given variable, the difference  
188 between the simulation by a GCM of a reference climate and a future climate are used to adjust  
189 sequences of catchment model driving variables. Whilst the CF approach offers a robust method to  
190 compare average outcomes from different climate models, it cannot provide any information on  
191 changes in hydrological extremes (Graham et al. 2007) because it assumes that the variability of the  
192 climate remains unchanged in the future. However, the CF method remains one of the most widely  
193 used for analysis of climate change impact on non-extreme variables and was used here to quantify  
194 changes in the monthly means of state variables. Change factors were used to perturb historic  
195 sequences of daily rainfall and monthly PE. The 2080s time horizon was selected because it has the  
196 strongest ratio between the signal of change and natural variability and the A2 emissions scenario  
197 (IPCC 2000) was applied because it is one of the most commonly considered scenarios. Simulated  
198 changes in mean monthly temperature and rainfall between the 1961–1990 and 2071–2100 periods  
199 for the A2 scenario were used. These factors were obtained for the 13 GCMs from the IPCC Data  
200 Distribution Center ([http://www.ipcc-data.org/ar4/gcm\\_data.html](http://www.ipcc-data.org/ar4/gcm_data.html)). Because the middle of the  
201 baseline period for the catchment simulation (1975–1997) differs from that of the climate model  
202 baseline (1961–1990) by 10.5 years, the monthly change factors were adjusted to account for this.  
203 This has been done by linearly scaling the factors assuming that the rate of change of temperature  
204 and precipitation is constant over time. The resulting perturbed time-series of driving climate  
205 variables were applied to the ZOODRM distributed recharge model, which calculated recharge for  
206 the transient groundwater flow model of the Almonte-Marismas aquifer.

### 207 **3.2. Recharge estimation**

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



209 2004). ZOODRM has been applied to a wide variety of hydrological regimes within temperate and  
210 semi-arid regions (Hughes et al. 2008; Jackson et al. 2011). The model uses a soil moisture balance  
211 approach based on the FAO method (FAO 1998) to calculate, evapotranspiration, surface runoff,  
212 and recharge using spatially distributed daily rainfall and potential evaporation time-series and land  
213 surface elevation, land-use, and geological data. A digital terrain model is used to route runoff  
214 across the land surface, which can subsequently infiltrate to form indirect recharge. The proportion  
215 of rainfall forming runoff is related to the topography, soil type, and geology.

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

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

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

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

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

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

261 aquifer.

### 262 **3.3. Almonte-Marismas groundwater flow model**

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

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

285 The hydraulic parameters of hydrogeological zones within the model, based on the geology  
286 (Figure 1b), were specified initially using data from more than 400 pumping tests but adjusted

287 during the calibration of the model against observed groundwater heads (Guardiola-Albert et al.  
288 2005). Model hydraulic conductivity values range from 0.001 to 50 m day<sup>-1</sup>. Initially a steady-state  
289 model was calibrated to historic mean groundwater levels in over 300 boreholes. Subsequently a  
290 time-variant model of the period 1975-1997 was developed. Simulated groundwater level time-  
291 series were compared to data from more than 1000 observation boreholes in the study area. The  
292 comparison between the simulated and observed groundwater levels at four of these boreholes is  
293 shown in Figure 3. A decrease in groundwater levels caused by the introduction of intensive  
294 irrigation is clearly identifiable within the marshland area (borehole 4).

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

### 305 **3.4. Groundwater simulations with GCM projected climate**

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

313 levels, and the components of the flow balance.

## 314 **4. Results**

### 315 **4.1. Projected climatology and impacts on groundwater recharge**

#### 316 *Temperature and potential evaporation*

317 Figure 4 shows the projected increase in mean monthly temperature from the baseline period  
318 (Table 2) for each of the 13 GCMs. All of the GCMs project a warming of at least 1.2°C for each  
319 month for the Doñana area. Between the months of November and March the increase, described by  
320 the average of the ensemble of models (black line in Figure 4), varies between 2.4 and 3.5°C.  
321 Between the months of April and October this ensemble average increase ranges from 4.2 to 4.7°C.  
322 Projected temperature increases are much higher during the summer, reaching a maximum value of  
323 7.4°C for the HADCM3 model projection. The CSMK3 model projects the smallest increase in  
324 temperature of between 1.0°C in February and 2.3°C in September.

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

#### 330 *Precipitation*

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

338 A number of GCMs project significant changes in precipitation during the winter. For

339 example, the IPCM4 model projects an increase of  $0.4 \text{ mm d}^{-1}$  in the months of February and  
340 March, HADCM3 an increase of  $0.4 \text{ mm d}^{-1}$  in December, and CNCM3 an increase of  $0.35 \text{ mm d}^{-1}$   
341 in September. A decrease of  $1.3 \text{ mm d}^{-1}$  is projected by the GFCM20 model in February and April  
342 and CNCM3 projects a decrease of  $1.2 \text{ mm d}^{-1}$  in November. All models project changes between -  
343  $0.11$  and  $+0.09 \text{ mm d}^{-1}$  in August.

#### 344 ***Recharge***

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

355 Annual recharge, expressed by the average of the ensemble of the 13 future simulations, is  
356 simulated to decrease by 35%. However the spread of the simulations ranges from a 57% decrease  
357 using the CNCM3 projection to a 14% decrease using the HADCM3 and NCPCM projections.  
358 Bootstrapped 95% confidence intervals on the ensemble mean of the percentage changes in mean  
359 annual recharge are  $-43$  and  $-27\%$ . These values are similar to that estimated by Custodio et al.  
360 (2007) in Doñana area, that suggest a decrease of recharge of 50% for an increase of temperature of  
361  $1^\circ\text{C}$ .

#### 362 **4.2. Climate change impacts on groundwater levels**

363 Figure 6 depicts differences in groundwater levels across the aquifer for December 2084 relative to  
364 the December 1979 in the baseline period. This date was selected as the monthly rainfall is close to

365 the average rainfall in the area and also because it follows a period which was not very dry or wet.  
366 The differences in groundwater level across the aquifer range between -17 and +2 m at this time.

367 Absolute differences in groundwater level between the baseline and future simulations across  
368 the northern part of the Almonte-Marismas aquifer and over some areas of the marshland are less  
369 0.5 m (see white areas in Figure 6). The largest reductions in groundwater level, of up to 17 m, are  
370 simulated across the unconfined groundwater mound in the El Abalario region. Other areas where  
371 there are significant simulated declines in the water table include the upper catchment of La Rocina  
372 stream (-1 to -5 m) and the irrigated Los Hatos region (-1 to -3 m). There is not a zone in which  
373 there is a significant rise of water levels in any of the simulations. The GFCM21 simulation  
374 produces the greatest decreases in water levels in comparison with the baseline simulation, with  
375 declines of up to 17 m. The NCPCM simulation is most similar to the baseline with decreases of up  
376 to 5 m in El Abalario. In general, for the 13 future simulations, water levels under the marshland  
377 tend to decrease between 0 and 6 m, but this fact has to be considered along with the reduction in  
378 discharge from the aquifer to the streams that flow into the marshland. In the irrigated Los Hatos  
379 area the maximum decline in groundwater level is 4 m under the GFCM21 simulation.

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

### 385 **4.3. Preservation of groundwater ecological discharges**

#### 386 ***Groundwater discharge to streams feeding the marshland***

387 For each future simulation temporal changes in the water balance have been calculated to examine  
388 the exchange of water between the aquifer and the main streams and drains that maintain the  
389 marshland: Guadiamar, Marismas, El Partido and La Rocina (Table 4). Whilst on average, flows  
390 from the streams to the aquifer do not change significantly with respect baseline values,

391 groundwater contributions to stream flows in the Marismas and La Rocina basins are considerably  
392 diminished by on average 53% and 36%, respectively. The discharge from the aquifer to the  
393 Guadiamar and El Partido basins, again as represented by the ensemble average, decreases by 7%  
394 and 15%, respectively, compared to the baseline values. Similar behaviour was also described in the  
395 preliminary study of Guardiola-Albert et al. (2009) in which climate change impacts were shown to  
396 have a more significant effect on groundwater outflows to rivers than river flows returns to the  
397 aquifer. This can be explained by the fact that during dry periods the streams are disconnected from  
398 the aquifer. During dry periods groundwater recharge and storage are reduced resulting in water  
399 table declines. As a result baseflow is reduced, and when the water table lies below the streambed  
400 there is a disconnection between the stream and the aquifer.

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

#### 408 ***Groundwater discharge to the sea***

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

#### 416 **5. Discussion**



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

430 Such declines in groundwater level result in a reduction of groundwater flow into the streams  
431 and to the marshland and an obvious reduction in the availability of water required to maintain  
432 aquatic life in the wetland and riparian ecosystems, especially in summer (Trick and Custodio 2004;  
433 Custodio et al. 2007). All 13 future simulations indicate decreases in discharge, of up to 68%, from  
434 the aquifer to the La Rocina and Marismas basins, which form the main water supplies to the  
435 marshland during the summer and which sustain important ecological systems. The consequences  
436 of these baseflow reductions, together with the decrease of direct discharge from aquifer to  
437 marshlands, could be drastic as it would reduce the availability of water that is necessary for the  
438 maintenance of aquatic life in the wetland and riparian ecosystems, especially during summer  
439 (Serrano et al. 2006). In addition, for the La Rocina stream, the amount of water flow has  
440 approximately halved within the last 20 years as a consequence of strawberry farm encroachment  
441 and the associated interception of groundwater. Hence, as discussed by Primack (2000) and WWF  
442 España (2006) climate change is another factor limiting the width of the riparian corridor along the

443 stream, and its effect must be considered within management plans developed by the water resource  
444 regulators and stakeholders. As suggested by Custodio et al. (1994), predicted decreases in  
445 discharge rates from the aquifer to the sea, of more than 50% by some models, would also result in  
446 the advance of saline water inland.

447 To put the potential effects of climate change on the Doñana wetland into context, a  
448 comparison has been made between the simulated impacts and current groundwater abstraction  
449 rates within the region. Simulated minimum, ensemble average and maximum decreases in total  
450 groundwater discharge (MODFLOW stream cell plus drain cell leakage) to the La Rocina, El  
451 Partido and Las Marismas basins are presented (Table 4). Groundwater abstraction in each of these  
452 catchments, for both irrigation and public supply, is also given. Mean historic total groundwater  
453 abstraction rates in the La Rocina, El Partido, Las Marismas and Guadiamar basins are 8.0, 0.3,  
454 18.6, and 0.1 hm<sup>3</sup>/year, respectively. These are equivalent to 24, 3, 47, and 1% of the historic  
455 groundwater discharge to each catchment, respectively. Decreases in groundwater discharge to the  
456 basins due to climate change are significantly greater than historic rates of abstraction in both the La  
457 Rocina and Las Marismas basins. In the El Partido basin one of the future simulations produces a  
458 4% increase in mean groundwater discharge but the worst case simulation produces a 73%  
459 reduction in groundwater discharge. The ensemble averages of the 13 future simulations represent  
460 decreases in groundwater discharge to these four basins of between 7 and 53% of mean historic  
461 discharge rates. These values provide the following useful guidelines to water and wetland policy-  
462 makers and stakeholders: (i) simulated climate induced decreases in groundwater discharge to the  
463 surface are substantive in comparison to the current wetland groundwater balance, (ii) these  
464 decreases are proportionally greater in the La Rocina and Las Marismas basin, than in the El Partido  
465 and Guadiamar basins, (iii) modelled reductions in groundwater flow to the surface associated with  
466 climate change are greater than current groundwater abstraction rates in most of the future  
467 simulations, and (iv) in the larger La Rocina and Las Marismas catchments, however, simulated

468 worst case decreases in groundwater discharge to the surface are 2.4 and 1.5 times greater than  
469 current abstraction rates, respectively.

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

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

493 Whilst these findings neglect other human induced effects such as changes in water use,

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

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Model	IPCC-DDC	Modelling Group	Country	Spatial Resolution
	Acronym			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

623 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 <sub>0</sub> (mm day <sup>-1</sup> )	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 <sub>0</sub> (mm day <sup>-1</sup> )	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 (°C)	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 <sup>-1</sup> )	2.48	2.45	0.98	1.22	1	0.3	0.03	0.09	0.66	1.81	2.86	3.45

625 Table 2 Monthly mean values of (i) measured reference evaporation ET<sub>0</sub> (mm day<sup>-1</sup>) at Los Palacios  
626 y Villafranca meteorological station for the period October 2000 to March 2007, (ii) calculated  
627 reference evaporation ET<sub>0</sub> (mm day<sup>-1</sup>) using the Blaney Criddle method, (iii) temperature (°C) at  
628 Los Palacios y Villafranca meteorological station for the period November 1978 to March 2007,  
629 and (iv) precipitation at Sanlucar Barrameda 'INM' meteorological station for the period 1975 to  
630 1997

631

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

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

634

	La Rocina basin	El Partido basin	Las Marismas basin	Guadamar 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
	Ensemble average	-12.2	-1.7	-20.7
	Minimum	-8.4	+0.4	-16.9

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

637

638 **Figures**

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

641 **Fig. 2** Groundwater model structure and boundary conditions

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

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

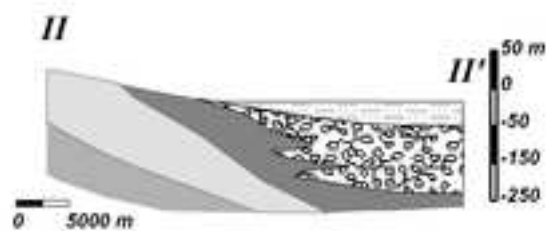
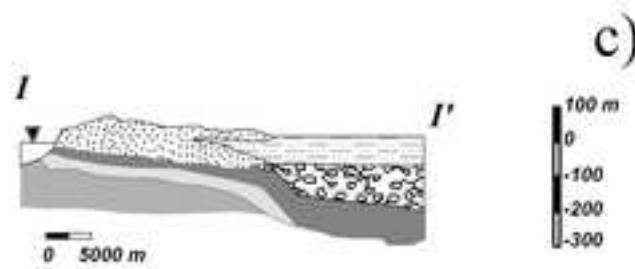
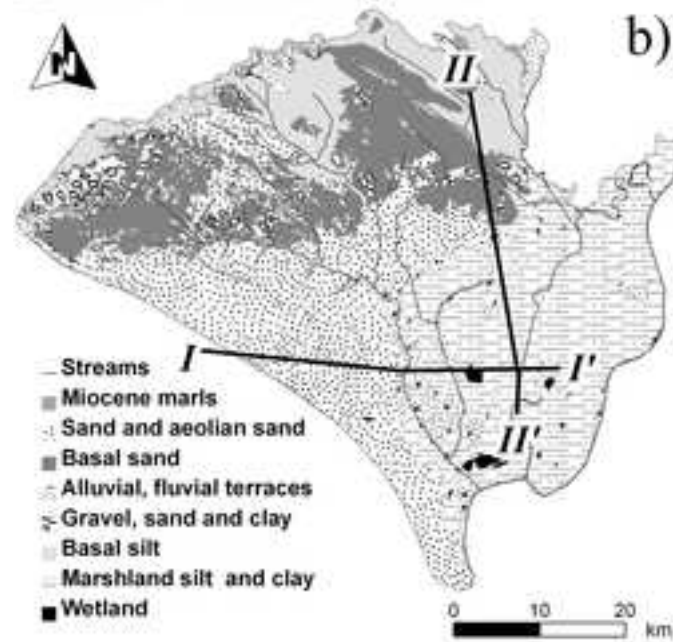
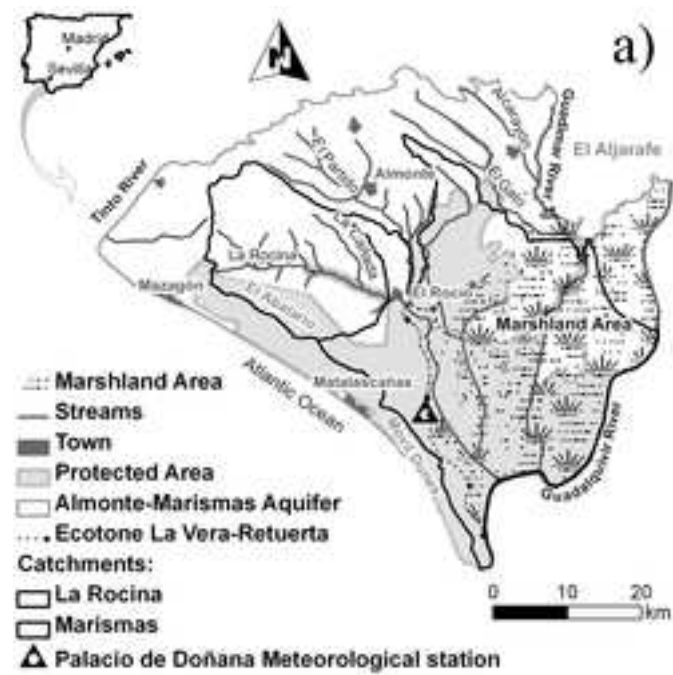
645 **Fig. 5** Simulated monthly mean recharge for the baseline (1975–1997) and 2080s time-slices under  
646 the A2 emissions scenario

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

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

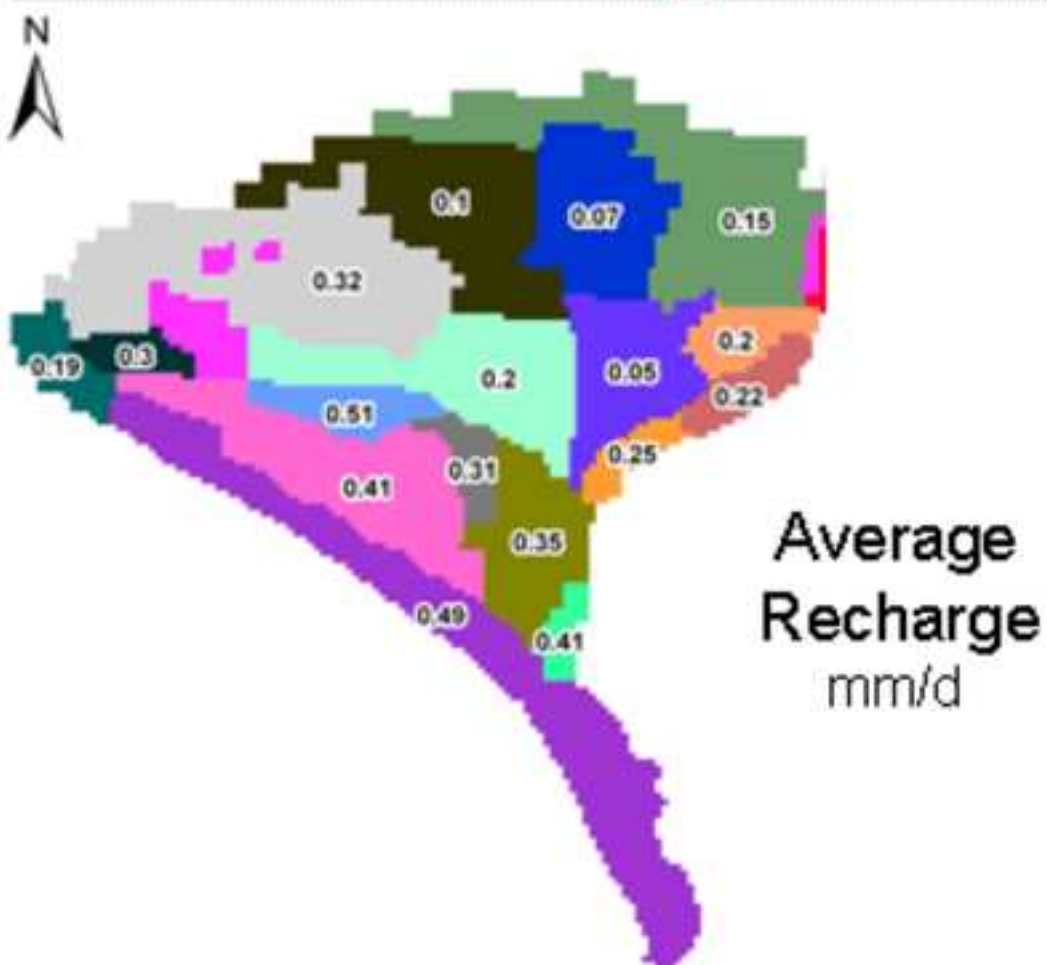
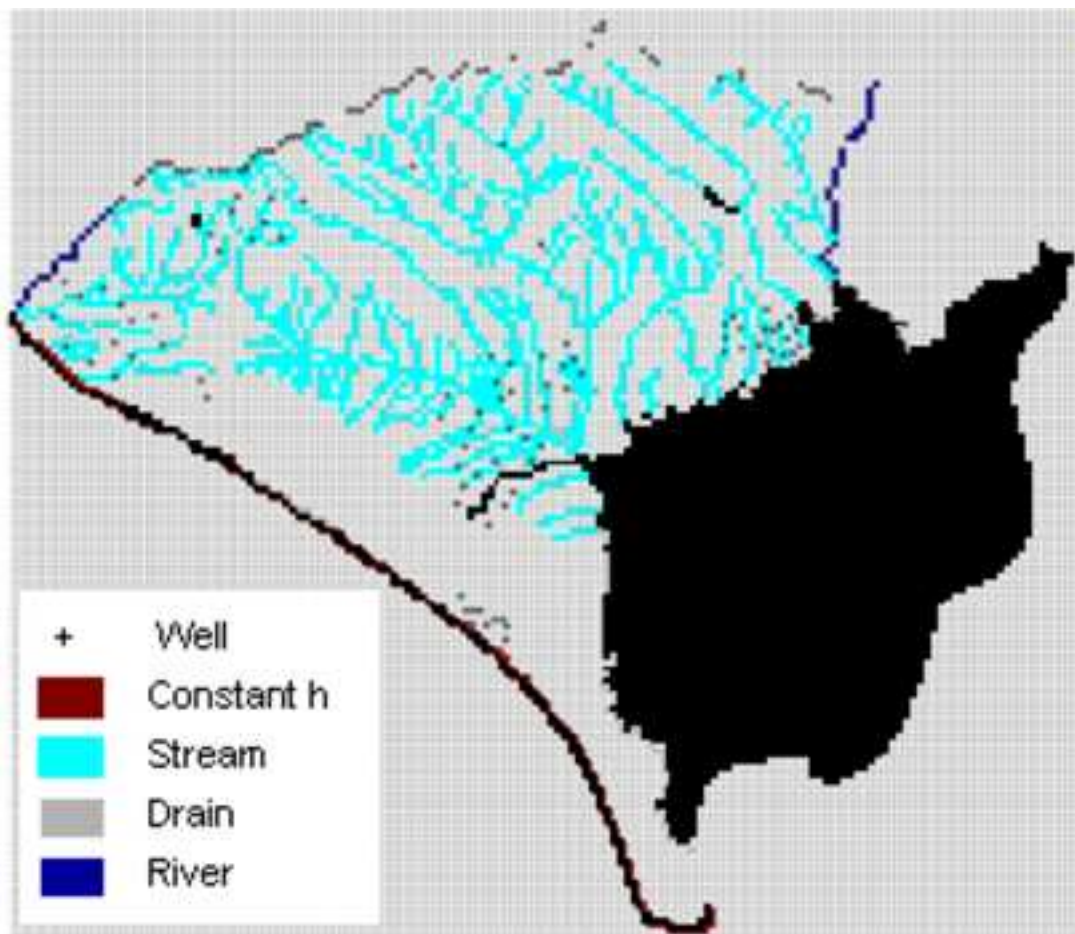
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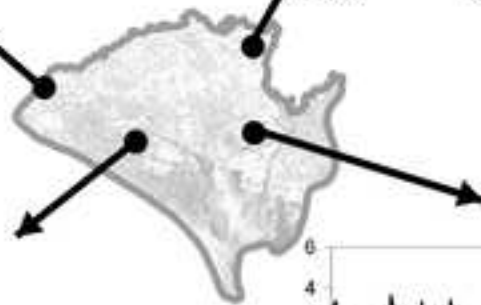
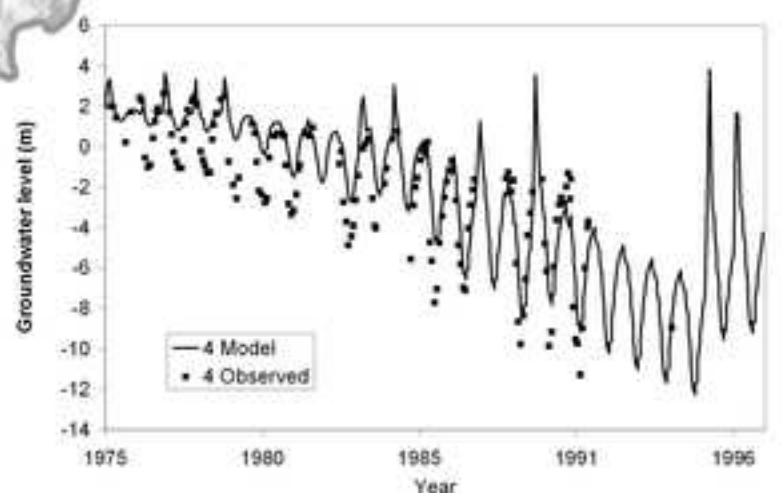
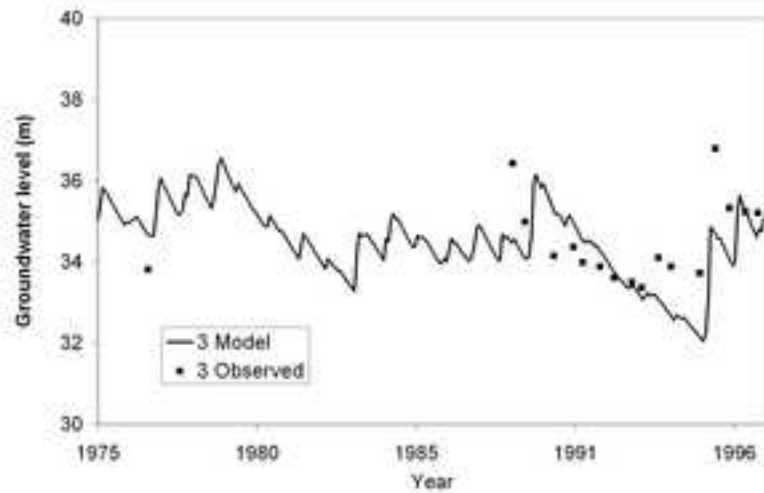
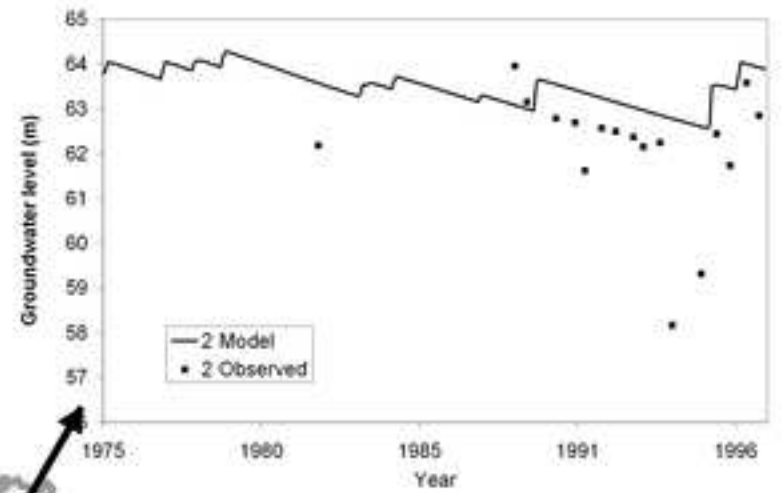
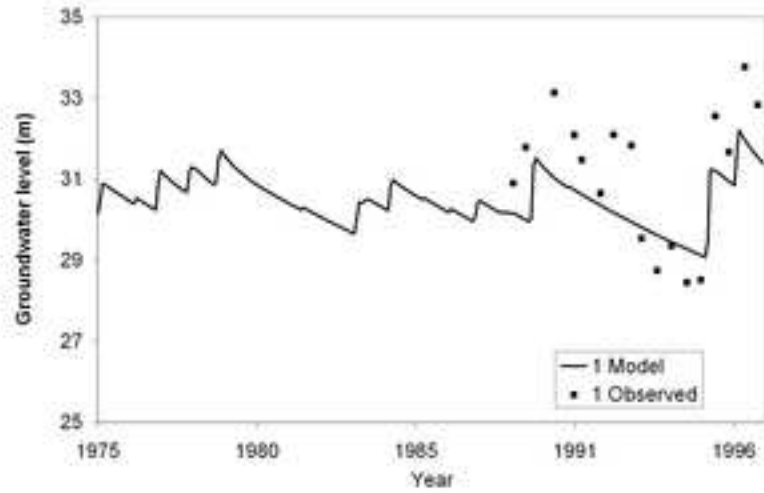


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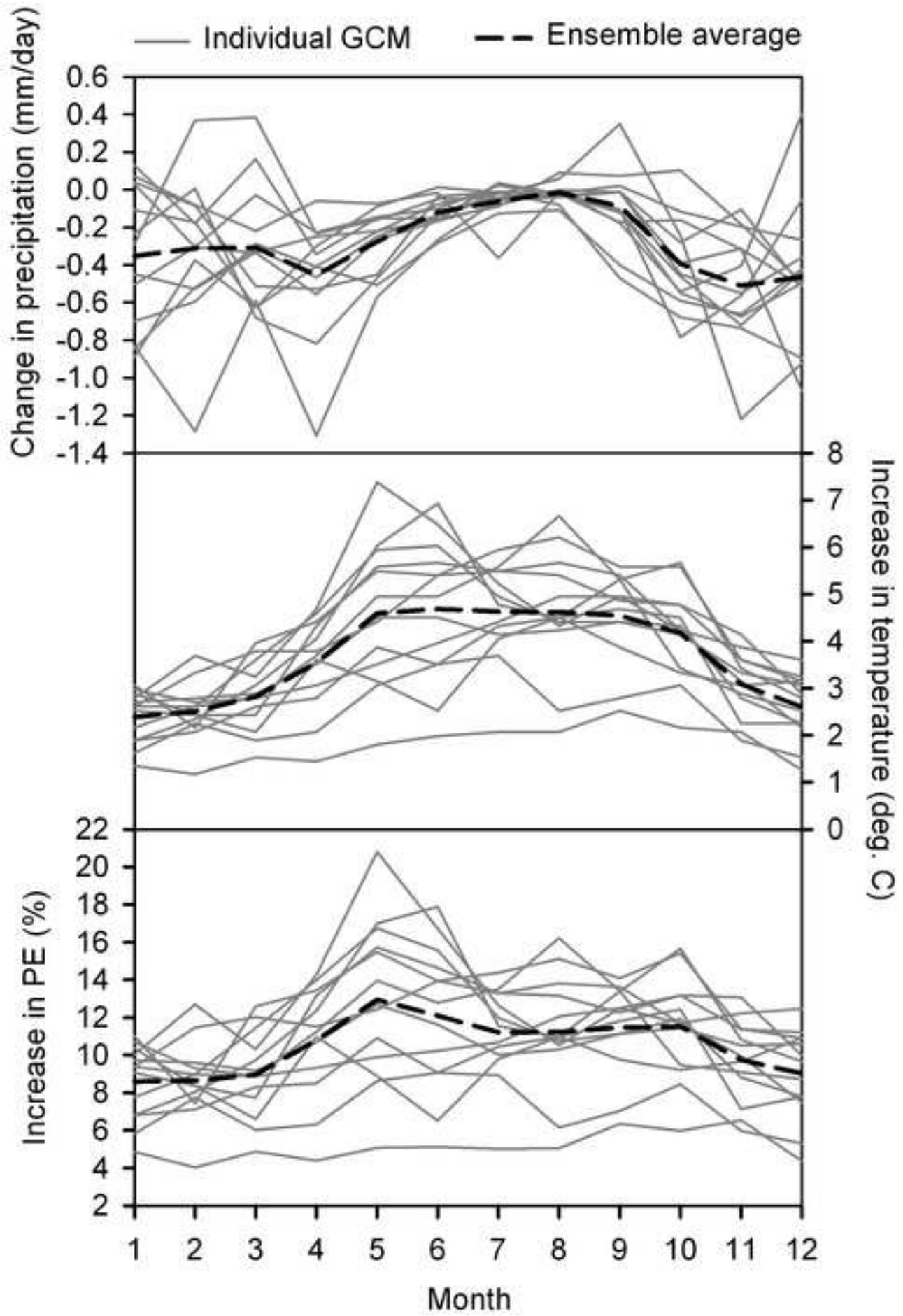
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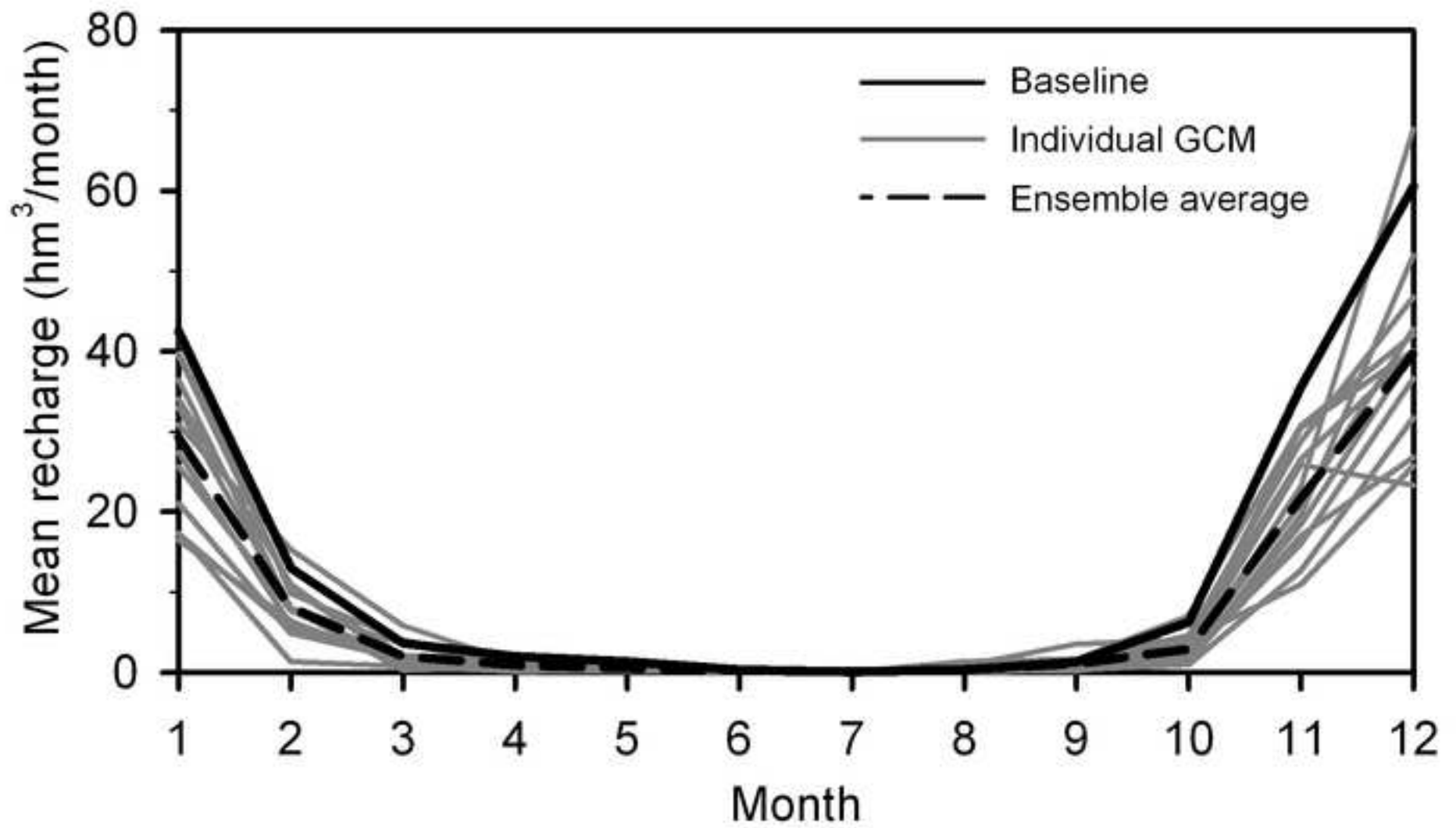


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# Groundwater level differences in December 2084 relative to December 1979

