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Investigating the respective impacts of groundwater exploitation and climate change on wetland extension over 150 years

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Antoine ARMANDINE LES LANDES^{1*}, Luc AQUILINA¹, Jo DE RIDDER¹, Laurent LONGUEVERGNE¹, Christian PAGÉ², Pascal GODERNIAUX^{1,3}.

¹Geosciences Rennes - CNRS - UMR 6118
University of Rennes 1
Bâtiment 14B
Campus Beaulieu
263 Avenue du Général Leclerc
35042 Rennes
France

* antoine.armandineleslandes@univ-rennes1.fr
(+33) 223 23 66 24
luc.aquilina@univ-rennes1.fr
laurent.longuevergne@univ-rennes1.fr

²European Center for Research and Advanced Training in Scientific Computing
42, avenue Gaspard Coriolis
Toulouse F-31057 Cedex 1
France
christian.page@cerfacs.fr

³Geology and Applied Geology
University of Mons
9, Rue de Houdain
B-7000 Mons
Belgium
Pascal.GODERNIAUX@umons.ac.be

*Corresponding author

1 Abstract

2 Peatlands are complex ecosystems driven by many physical, chemical, and biological
3 processes. Peat soils have a significant impact on water quality, ecosystem productivity and
4 greenhouse gas emissions. However, the extent of peatlands is decreasing across the world,
5 mainly because of anthropogenic activities such as drainage for agriculture or groundwater
6 abstractions in underlying aquifers. Potential changes in precipitation and temperature in the
7 future are likely to apply additional pressure to wetland. In this context, a methodology for
8 assessing and comparing the respective impacts of groundwater abstraction and climate
9 change on a groundwater-fed wetland (135 km²) located in Northwest France, is presented. A
10 groundwater model was developed, using flexible boundary conditions to represent surface-
11 subsurface interactions which allowed examination of the extent of the wetland areas. This
12 variable parameter is highly important for land management and is usually not considered in
13 impact studies. The model was coupled with recharge estimation, groundwater abstraction
14 scenarios, and climate change scenarios downscaled from 14 GCMs corresponding to the
15 A1B greenhouse gas (GHG) scenario over the periods 1961-2000 and 2081-2100. Results
16 show that climate change is expected to have an important impact and reduce the surface of
17 wetlands by 5.3 % to 13.6 %. In comparison, the impact of groundwater abstraction (100 %
18 increase in the expected scenarios) would lead to a maximum decrease of 3.7 %. Results also
19 show that the impacts of climate change and groundwater abstraction could be partially
20 mitigated by decreasing or stopping land drainage in specific parts of the area. Water
21 management will require an appropriate compromise which encompasses ecosystem
22 preservation, economic and public domain activities.

23 **Keywords:** Peatlands, groundwater, wetlands, humid zone, climate change, groundwater
24 pumping

25 1. Introduction

26 Peatlands are complex and fragile ecosystems driven by many physical, chemical, and
27 biological processes. Numerous studies have provided a comprehensive understanding of
28 wetland hydrology, especially regarding the interactions between surrounding aquifers and
29 surface water networks (Bradley, 2002; Frei et al., 2010; Grapes et al., 2006; Lischeid et al.,
30 2010; Reeve et al., 2000; van Roosmalen et al., 2009; Wilsnack et al., 2001; Winter, 1999).
31 Because peat soils can serve as sinks, sources, and transformers of nutrients and other
32 chemical contaminants, they have a significant impact on water quality, ecosystem
33 productivity and greenhouse gas emissions (Hemond and Benoit, 1988; Johnston, 1991;
34 Kasimir-Klmedtsson et al., 1997; Roulet, 2000). The extent of peatlands is tending to
35 decrease worldwide, (Estimated to 6 % over the period 1993-2007 - Prigent et al. (2012)).
36 However, peatlands are considered as important carbon reserves (15-30 % according to Botch
37 et al. (1995); Turunen et al. (2002)), and important potential sources of CO₂ even though they
38 cover only 3 to 4 % of emerged areas on the earth. As the oxygen concentration in peat
39 increases due to water drawdown, surface decomposition is enhanced by bacterial aerobic
40 processes (Holden et al., 2004). Oxygen enhances organic matter mineralization, leading to
41 CO₂ release to the atmosphere and nutrients production, particularly carbon-bound nitrogen
42 and sulphur. Decreasing groundwater levels can also cause land subsidence, due to the
43 reorganization of the peat structure (Silins and Rothwell, 1998).

44 The hydrology of the peat layer and extent of this peat area are impacted by drainage for
45 agriculture, groundwater abstractions in underlying aquifers and climate change. The general
46 impact of climate change on hydrological systems has been studied, focusing on surface water
47 (Christensen et al., 2004; Fowler et al., 2007a), and more recently on groundwater reserves
48 (e.g. Goderniaux et al., 2009; Goderniaux et al., 2011; Green et al., 2011; Herrera-Pantoja and
49 Hiscock, 2008; Holman et al., 2011; Scibek et al., 2007; Woldeamlak et al., 2007). However,

50 few studies have addressed the impact of climate on the evolution of peatlands, which are
51 specific ecosystems located at the interface between surface water and groundwater.
52 Moreover, the respective impacts of climate change and anthropic water abstraction on
53 wetlands have not been investigated and compared.

54 Peatlands are commonly observed in lowland areas where shallow gradients, impermeable
55 substrates or topographic convergence maintain saturation. Peatland classification is generally
56 related to two fundamental factors: source of nutrients and source of water. Bogs or
57 ombrotrophic peatlands are dependent on precipitation for water and nutrient supply, whereas
58 minerotrophic peatlands or fens rely on groundwater (Johnson and Dunham, 1963). As a
59 consequence, two different points of view have generally been adopted in studies of the
60 impact of climate change. Thompson et al. (2009) performed an impact study on the Elmley
61 marshes (8.7 km²) in England using a coupled surface-subsurface model, where subsurface is
62 represented by a single uniform layer. In their study, precipitation and evapotranspiration
63 were the main hydrological processes, due to the impoundment of the marshes within
64 embankments and their low hydraulic conductivity. Conversely, other studies emphasized the
65 importance of the interactions with groundwater. Candela et al. (2009) developed a
66 groundwater model (415 km²) for a basin in the Island of Marjorca (Spain), to assess the
67 impact of climate change on groundwater resources and on springs discharging into a smaller
68 wetland area. Herrera-Pantoja et al. (2012) used a generalized groundwater model of eastern
69 England wetlands to assess climate change impacts on water levels and their consequences on
70 typical plant species. Barron et al. (2012) assessed the risks for wetlands and groundwater-
71 dependent vegetation in the southern half of the Perth Basin (~20000 km², Australia) under
72 future climate change scenarios. Their study is based on a global approach using coefficients
73 of groundwater sensitivity to climate change, and a regional-scale groundwater model.

74 In this study, we considered peatlands as components of a complex system where the different
75 surface and subsurface compartments interact. Our general objective was to evaluate and
76 compare the competing impacts of climate change and water abstraction activities on
77 groundwater storage and the extents of wetland areas. We focused on a 135 km² peatland area
78 in the Cotentin marshes (northwest France). Our three main objectives were: (i) to understand
79 surface-subsurface connectivity and associated wetland hydrological sensitivity, (ii) to
80 quantify the impact of projected increases in groundwater abstraction, and (iii) to estimate the
81 impact of climate change at the end of this century. These objectives have been attained by
82 using a 3D groundwater model for the Cotentin wetland area.

83 **2. Study area**

84 **2.1. The Cotentin marshes**

85 The Cotentin marshes are located within a large watershed in Normandy (Northwest France,
86 see Figure 1). The study area is situated within a natural reserve, and extends over
87 approximately 135 km². Topography ranges from 0 to 30 m above sea level. Mean annual
88 precipitation and potential evapotranspiration for the period 1946-2010 (from two climatic
89 stations, Figure 1) were 910 mm/yr and 630 mm/yr, respectively. In the lowland areas, the
90 vast wetlands and peatlands partly consist of peat soils and are located along 3 main rivers:
91 the 'Sèves' in the North, the 'Holerotte' in the West, and the 'Taute' in the South (Figure 1). As
92 suggested by hydrologic fluxes and chemical features (Auterives et al., 2011), this wetland
93 area is closely related to groundwater. It is connected with an underlying highly transmissive
94 aquifer and surface-water bodies are integral parts of the groundwater flow systems. For
95 several centuries, this large wetland has undergone numerous disturbances. In the 18th century
96 the wetland was flooded 9 months per year (Bouillon-Launay, 1992). Since 1712, a human-
97 controlled drainage system has gradually been set up. From 1950 until now, the flooding

98 season has been reduced to only 3 months on average due to agricultural constraints. The top
99 peat profile is thus subjected to longer periods of desiccation. Beside agricultural pressure, the
100 underlying aquifer is also used as a drinking water supply, since 1992. Due to an increasing
101 demand for high-quality water, the authorities plan to increase groundwater abstraction in the
102 near future. The Cotentin peatlands are nevertheless also classified as a natural reserve for
103 specific wildlife and plant species. Additionally, geotechnical perturbations such as the
104 collapse of parts of houses or fissures in constructed walls have also been reported along the
105 border of the peatland. These perturbations have generated public manifestations, and the
106 filing of legal claims in early 2012. It was often claimed during these manifestations that
107 groundwater extraction was responsible for the observed damage. As a consequence, the
108 Cotentin marshes are at the centre of different interests, which must be integrated by
109 stakeholders into their management plans: ecological activities through the preservation of
110 wetlands, economic activities through the preservation of farmland, and public domain
111 activities through the distribution of drinking water.

112 **2.2. The Sainteny-Marchésieux aquifer**

113 The geology of the Sainteny-Marchésieux study area, located in the Cotentin marshes,
114 corresponds to a graben structure (Baize, 1998), bounded by NE-SW and NNW-SSE faults
115 (Figure 2), with a depth of 150m. The substratum is considered as impermeable and
116 corresponds to Precambrian geological formations to the south and west and Permo-Trias to
117 the east and the north (Figure 2). Within the graben structure, two different aquifer areas can
118 be distinguished (Figure 2). (1) The Sainteny aquifer in the northwest extends over
119 approximately 35 km². It consists of shelly sands up to 100 m thick, characterized by
120 relatively high hydraulic conductivity. (2) The Marchésieux aquifer, in the south, extends
121 over approximately 100 km². This area is characterized by different lithologies, including
122 sandstones, shales and sandy loams. These formations have a maximum total thickness of

123 150 m and are considered less permeable than the shelly sands of the Sainteny aquifer. These
124 thick formations are overlain by (1) Holocene peats, ranging in thickness from 1 to 10 meters
125 in the wetland area (Figure 1) and (2) by sands (up to 10 m) elsewhere. According to the
126 observed groundwater heads and the hydraulic conductivity of these lithologies, the aquifer is
127 considered as confined below the peatlands and unconfined below the sands.

128 Generally, groundwater flows from southwest to northeast and the aquifer is drained by a
129 dense hydrographic network. High and low areas act as recharge and discharge zones,
130 respectively, (as conceptually shown in Figure 3). Currently, groundwater is predominantly
131 abstracted in the Sainteny aquifer, with about 5 million m³ pumped each year in 5 different
132 existing wells (Figure 1). The Marchésieux aquifer exploitation is limited to a single existing
133 well, with a pumping rate of about 0.14 million m³ per year. Groundwater abstraction
134 represents approximately 9 % of the total recharge rate.

135 In the north of the catchment, the peatlands in the 'Bapte' area (Figure 1) were exploited
136 from the 1950s to 2006. Peat extraction implied a considerable lowering of the water table.
137 Currently, a large pit of about 0.4 km² remains and the average water level in this zone is
138 artificially maintained about 4.9 m below the ground surface to avoid flooding of certain areas
139 of farmland.

140 **3. Modeling**

141 *3.1 Model implementation*

142 The 3D groundwater model has been developed with the Modflow 2005 finite difference code
143 (Harbaugh, 2005). The modeled area corresponds to the Sainteny-Marchésieux
144 hydrogeological catchment which is globally defined by the limits of the graben structure.
145 Boundary conditions along the model limits have been implemented as follows (Figure 2):

146 - Sections B-C, D-E and F-A correspond to the interface between bedrock and
147 sediments inside the graben. According to the geology and measured groundwater
148 levels, this interface is considered as impermeable. A no-flow boundary condition is
149 prescribed along these sections.

150 - Section A-B corresponds to a stream section, which is considered as a main drainage
151 divide. A no-flow boundary condition is implemented along this stream section.

152 - Sections C-D and E-F also correspond to the graben limits but measured groundwater
153 levels show that groundwater fluxes, from the adjacent geological formation, feed the
154 aquifer. Along these sections, a groundwater flux, equal to the recharge rates times the
155 upstream areas, is prescribed.

156 Inside the modeled area, a seepage boundary condition (head dependent flux – ‘Drain
157 package’) is applied at the ground surface. This boundary condition enables groundwater to
158 leave the system only when the simulated hydraulic head is above the topographic surface,
159 according to a conductance coefficient. This type of boundary condition is particularly useful
160 in this wetlands context, where the extent of the discharge areas is dependent on recharge
161 rates. Fluxes abstracted for drinking water distribution are applied to the nodes corresponding
162 to the pumping wells (see section 3.5.1). Finally, a prescribed head boundary condition is
163 applied to the Baupte peatland extraction area (0.4 km²) where the water level is artificially
164 maintained at 4.9 m below the ground surface. This boundary condition can be used in this
165 circumstance because the calculated heads are never lower than the bottom of the peat
166 exploitation. The bottom of the model is considered as impermeable, and implemented with a
167 no-flow boundary condition.

168 *3.2 Model Discretization*

169 The study area was discretized using 90 by 90 m cells and 6 layers, with a total number of
170 approximately 100,000 cells. The top of the first layer corresponds to the topographic surface,
171 extracted from a digital elevation model of the region. This first layer is 10 m thick and
172 corresponds to the quaternary peats and upper sands. The interface between the first and
173 second layer corresponds to the top of the aquifer which is composed of shelly sands,
174 sandstones and sandy loams (see Section 2). The depth of the aquifer base has been defined
175 from borehole data and ranges from 70 m to 150 m below sea level. Five horizontal finite
176 difference layers are used to represent this aquifer.

177 *3.3 System stresses*

178 Recharge and wells pumping rates are applied as input to the model. Pumping rates are
179 calculated from the abstracted groundwater volumes, which have been collected for years by
180 the regional water agencies. Recharge values are applied on the whole modeled area. They
181 are computed externally using a water balance method, based on a modified version of the
182 parsimonious monthly lumped model GR2M (Mouelhi et al., 2006). The GR2M model
183 obtained one of the best performances in a benchmark test of 410 basins throughout the world
184 in different climatic contexts, as compared to 9 other models with generally more parameters
185 (Mouelhi et al., 2006). The GR2M model has been designed to separate rainfall into actual
186 evapotranspiration, surface runoff and transfer to the routing store, which is interpreted here
187 as aquifer recharge (see model description at <http://www.cemagref.fr/webgr/IndexGB.htm>).
188 Observed rainfall and potential evapotranspiration, provided by 'Meteo France', are used as
189 GR2M inputs. The GR2M model is calibrated to monthly surface runoff data, which are
190 calculated by baseflow separation from measured river flow rate time series. Data are
191 available over a time frame ranging from January 1999 to December 2000 and January 2003

192 to December 2007 and includes both wet (1999-2000) and very dry years (2003-2004), which
193 maximizes the descriptive ability of the model over a large interval of climatic fluctuations.
194 This is particularly important in the context of future climate change where applied stresses
195 typically go beyond the calibration interval. The calibration is limited to a 1-parameter
196 calibration process, which is here the soil storage capacity, and carried out on the square root
197 of surface runoff to allow equal weight to high and low flow situations (Oudin et al., 2006). In
198 the optimization process, the Nash-Sutcliffe criterion (Nash and Sutcliffe, 1970) was used as
199 the objective function, and supplemented with the constraint to conserve the total amount of
200 surface runoff ($\sum Q_{obs} / \sum Q_{sim} = 1$), where Q_{sim} and Q_{obs} are simulated and observed surface
201 runoff (Figure 4). The Nash-Sutcliffe criterion is 0.70 and the calculated annual recharge
202 ranges from 164 mm/yr to 338 mm/yr. On an annual basis, the total amount of water in rivers
203 is also preserved. The sum of simulated surface runoff and recharge is very close to the
204 observed flow rate in rivers. For the wet (1999-2000) and dry (2003-2004) years, the error is
205 equal to 2 and 4 %, respectively. Checking this relation prevents under or overestimation of
206 calculated annual recharge due to errors on the actual evapotranspiration term. This calibrated
207 'GR2M' mass-balance model is subsequently used to externally calculate the recharge to be
208 applied as input to the hydrological Modflow model, for historic and future climatic scenarios
209 (see Section 3.5).

210 ***3.4 Calibration and validation of the hydrological model***

211 The hydrological Modflow model was calibrated to the observed *i*) aquifer hydraulic heads,
212 *ii*) spatial distribution of wetland area and *iii*) *stream base-flow*. The calibration was
213 performed in steady state conditions for two humid and dry contrasted years, 1999-2000
214 (R=338 mm/yr) and 2003-2004 (R=164 mm/yr), respectively, for which daily climatic data
215 were available. The calibration was performed automatically using the PEST module coupled

216 with Modflow, and by adjusting the hydraulic conductivities of the different geological
217 formations within specific ranges provided by field tests (Auterives, 2007; Auterives et al.,
218 2011). This calibration was validated using data from the hydrologic year 2006-2007
219 ($R=263$ mm/yr), which is close to the 1961-2000 average precipitation and temperature
220 statistics (where $R=250$ mm/yr). Results of the calibration are shown in Table 1, Figure 5 and
221 Figure 6, for hydraulic conductivities, groundwater levels and wetland surface, respectively.
222 Table 1 shows the calibrated hydraulic conductivities of the geological formations represented
223 in the model. The seepage conductance is set to a high value, calculated from a hydraulic
224 conductivity which is significantly higher than the hydraulic conductivity of the geological
225 layers. Figure 5 presents residuals for the groundwater levels, calculated as the difference
226 between the observed and simulated values. Figure 6 shows the observed and simulated
227 wetland areas. The “observed wetland areas” are given by cartographic data (data base from
228 the local conservatory park: “Parc Naturel des marais du Cotentin et du Bessin”) which are
229 representative of the mean climatic conditions of the time period 1961-2000. These wetlands
230 are defined as zones where a groundwater level close to the soil surface is maintained during a
231 large part of the year. The “simulated wetland areas” are calculated from the model outputs. A
232 finite difference cell is considered as part of the wetland area when the simulated groundwater
233 level is less than 0.5 m below the ground surface. Observed groundwater discharge volumes
234 are calculated as the difference between the main stream inlets (Sèves, Holerotte and Taute)
235 and outlets (Sèves and Taute) volumes, where gauging stations are located (Figure 1). The
236 errors between observed and simulated volumes of groundwater drained from the aquifer to
237 the surface domain (through the seepage boundary condition) are below 5 %. The volume of
238 water extracted by the prescribed head boundary condition is equivalent to the quantity of
239 water pumped by the Baupte peatland manager: approximately 10 million m^3 each year.

240 3.5 Future scenarios

241 Future scenarios for groundwater abstraction and climate change were applied as input to the
242 calibrated model, to assess their respective impacts on the catchment, with particular focus on
243 wetland extension. These scenarios are compared with a reference simulation corresponding
244 to the average recharge and groundwater abstraction for the period 1961-2000. The reference
245 recharge is 250 mm/yr and the abstracted groundwater volumes are 5 million m³/yr. The
246 climate change, groundwater abstraction and management scenarios considered in this study
247 are summarized in Table 2.

248 3.5.1 Future groundwater abstraction

249 Groundwater abstraction volumes that will be required in the future are defined from
250 projections made by the local water agency. Four different scenarios are tested, considering an
251 increase in groundwater demand of 10 %, 20 %, 50 % and 100 %, relative to the current
252 volumes (5 million m³/yr) (Table 2). Two different management plans are considered and
253 tested with the model. The first plan consists in applying the increase in groundwater demand
254 to the pumping rates of the 6 existing wells currently used (Figure 1) (Scenarios 1 to 4 in
255 Table 2). The second plan consists in using two new wells located in the Marchésieux aquifer
256 (Figure 1) to support the increase in groundwater demand (Scenarios 5 to 8). In this second
257 plan, the abstraction flow rates in the existing wells are kept constant.

258 3.5.2 Climate change

259 Climate change impact studies cannot directly use the output of global climate models (GCM)
260 because of discrepancies between the extent of the impact model (135 km²) and the horizontal
261 resolution of these numerical models (~250 km, see Solomon et al. (2007)). Downscaling
262 methodologies are commonly used to overcome this problem. Such methods are either
263 dynamically and/or statistically based. In the current study, DSCLIM, a statistical

264 downscaling methodology developed at CERFACS was applied to work at an 8 km
265 resolution. This method is based on the physical relationship between large-scale atmospheric
266 circulations and the local-scale climate (Boé et al., 2009; Fowler et al., 2007b; Pagé et al.,
267 2009). Although downscaling methods are also a source of uncertainty (Fowler et al., 2007a),
268 we chose to focus on climate model uncertainty, which has been shown to be conservative for
269 hydrological impact studies in the French context (Ducharne et al., 2009). This was applied to
270 produce climate scenarios for specific chosen locations in France. Using this methodology, 14
271 GCMs were downscaled from the 2007 CMIP3 database for the A1B greenhouse gas (GHG)
272 scenario over the periods 1961-2000 and 2081-2100, as shown in Table 3 (see Solomon et al.,
273 2007, for details about the GCMs). Scenario A1B is a sub-category of storyline A1. The A1B
274 scenario was selected because of the availability of several A1B downscaled scenarios, which
275 make possible the evaluation of uncertainties.

276 In the framework of this study, precipitation and PET time series for 64 downscaled cells
277 corresponding to the Cotentin region, for the 14 GCMs, and the periods 1961-2000 and 2081-
278 2100, were extracted. The period 1961-2000 is considered as the reference case (Table 3). For
279 each cell, each climatic model and each period, the mean annual recharge is calculated using
280 the calibrated GR2M module. The mean recharge rate for the modeled area is then calculated
281 as the average of the 64 cell results. Figure 7 shows temperature and precipitation changes for
282 the period 2081-2100. Compared to the reference period, the mean annual temperature is
283 expected to increase by between 1.3 and 3.7 °C, and annual precipitation is expected to
284 decrease by between 1.8 and 21.3 %. The calculated recharge for the reference case is
285 250 mm/yr. All climatic projections induce a decrease in recharge rate ranging from 22 % to
286 61 %, with an average of 40 % (Table 3). Scenarios 'csri_mk3_0' and 'ipsl_cm4' give the
287 minimum and maximum decreases in recharge, respectively.

288 3.5.3 *Coupling climate change, groundwater abstraction and management*

289 In this impact study, the 3 most contrasted climatic projections, from the 14 downscaled
290 GCMs, are used as input for the hydrological model to investigate the variability between the
291 climate change models (Table 3):

- 292 ▪ the most favorable ('csri_mk3_0', termed scenario A, R=194 mm/year)
- 293 ▪ the most unfavorable ('ipsl_cm4', termed scenario N, R=97 mm/year)
- 294 ▪ the average scenario ('miroc3_2_medres', termed scenario H, R=148 mm/year).

295 Each climate scenario is coupled with 4 groundwater extraction scenarios (increase of 10, 20,
296 50 and 100 %), according to the actual trend in water demand and consumption. Each of these
297 combinations is applied to the two abstraction-management schemes described above:
298 pumping increase in Sainteny (scenarios 12 to 23) or Marchésieux (scenarios 24 to 35) sub-
299 catchments.

300 One of the main objectives was to provide insights into wetland management solutions to
301 mitigate climate change and anthropic impacts. Exploitation of the Bauppte peatland (Figure 1)
302 stopped in 2006 but pumping is maintained to avoid flooding the surrounding fields which are
303 used for agriculture. An efficient management of Bauppte might therefore provide a solution to
304 reduce negative anthropogenic impacts i.e. water drawdown. The feasibility of this
305 management scheme was studied by complementing the previous scenarios with additional
306 scenarios where pumping is stopped in the Bauppte peat exploitation. This stop is simulated in
307 the model by removing the prescribed head boundary condition over the 0.4 km² 'Bauppte'
308 area. As in the previous cases, the simulation was applied to the two abstraction-management
309 schemes i.e. increased pumping in the Sainteny (scenarios 39 to 50) or Marchésieux
310 (scenarios 51 to 62) sub-catchments. Three additional scenarios were tested to estimate the
311 respective impacts of past climate change (increase of 1°C between 1950 and 2012) and past

312 anthropogenic activities (Pumping of Baupte and groundwater abstraction) in relation to the
313 current situation.

314 **4. Results**

315 The wetlands compartment corresponds to a natural aquifer outflow and, as shown in the next
316 section, any change in the aquifer recharge or groundwater abstraction is likely to affect
317 wetland area. Future scenarios for groundwater abstraction, climate change and management
318 were then applied as model input. All results for future scenarios were compared to the
319 reference model (1961-2000) with particular focus on the wetland surface area and on water
320 level changes. A summary of these results is presented in Figure 8 and Figure 9. Proportions
321 of the different water balance terms for some scenarios are given in Table 4.

322 *4.1 . Wetland surface reduction*

323 Figure 8 shows the proportion of wetland surface area for the reference model (1961-2000),
324 for future groundwater abstraction scenarios, climate change scenarios (2081-2100) and
325 coupled scenarios. For the reference model, the proportion of wetland area is equal to 24.4 %
326 of the total area. This proportion clearly decreases with increasing groundwater abstraction. If
327 these new groundwater volumes are pumped in existing wells, the wetland area decrease
328 ranges from -0.02 % to -3.7 % (0.03 km² and 5.05 km²), according to the magnitude of
329 groundwater abstraction. Conversely, if additional pumping is carried out in new wells in the
330 Marchésieux sub-basin, the impact on wetland area is less important and ranges from -0.04 %
331 to -1.56 % (0.05 km² and 2.1 km²). It is partly due to the better distribution of abstracted
332 volumes over the whole area but also because of the groundwater fluxes entering through the
333 southwest catchment limits which feed the aquifer.

334 Simulations of the impacts of climate change indicate a significant reduction of wetland
335 surface area by the end of the century (2081-2100), which is correlated to the decrease of

336 recharge (ranging from -22 % to -61 %, see Table 3). Considering unchanged groundwater
337 abstraction, reduction of the wetland surface area ranges from -13.64 % (18.4 km²) for the
338 worst climatic scenario N (recharge of 97 mm) to -5.34 % (7.2 km²) for the most favorable
339 scenario A (recharge of 194 mm). These results also provide important information about the
340 respective influence of groundwater abstraction and future climate change. On the scale of the
341 modeled area as a whole, climate change generally induces a larger reduction in wetland area,
342 than any of the groundwater abstraction scenarios. Although scenario A is the most
343 “favorable” climatic scenario, the impact on wetland surface area is actually more important
344 than the worst groundwater abstraction scenario. As shown in Figure 8, the combined impact
345 of climate change and groundwater abstraction is even more important and ranges from -
346 5.36 % to -16.04 %, depending on the climate change scenario and location of the pumping
347 wells.

348 Regarding water balance terms, fluxes entering the domain correspond to the recharge applied
349 on the top cells and groundwater entering by specified flux boundary condition (See Section
350 3.1). These specified groundwater fluxes represent 36 % of total water influx in the modeled
351 domain. Fluxes leaving the domain correspond to the groundwater discharge, pumpings in the
352 public water distribution wells and pumpings in the Baupte peat exploitation. For the
353 reference scenario, these terms correspond to 72 %, 9 % and 19 % of total influx,
354 respectively. Numerical simulations allow quantifying the absolute and relative evolution of
355 these terms considering various stresses (Table 4). For climate change scenarios with
356 unchanged groundwater abstraction, absolute values of all terms logically decrease with
357 recharge and more extreme climate change. However, the proportion of abstracted
358 groundwater (public wells and Baupte) relatively to total influx increases to the detriment of
359 groundwater discharge. For the worst climate change scenario (scenario N), groundwater
360 discharge is only 32.1 % of total influx. In cubic meters, this represents a decrease of more

361 than 80 % compared to the reference simulation. Finally, Table 4 also shows that the decrease
362 of total water influx in climate change scenarios is greater than groundwater abstraction by
363 public wells, which partly explains the preponderant impact of climate change on wetland
364 areas. Relations between input stresses and hydrogeology variables are however complex and
365 dependent on many parameters (such as geology, topography, locations of pumping wells), so
366 that numerical modeling is required for an objective impact quantification.

367 *4.2 Wetland spatial distribution*

368 Previous analyses provide overall information on the scale of the modeled area. However, the
369 different scenarios also imply different impacts in terms of the distribution of drawdown
370 within the wetlands (Figure 9).

371 Increasing pumping rates by 50 % in existing wells induces a water level decrease of between
372 25 cm and 40 cm in the Sainteny Northern wetland, while water levels are not significantly
373 affected in the Marchésieux Southern wetland (Figure 9A, Scenario Pumping +50 % with
374 existing wells, Scenario 3). Conversely, increased pumping in new wells located in the
375 Marchésieux basin leads to a better distribution of the impacts (Figure 9B, Scenario Pumping
376 +50 % with existing and 2 new wells, Scenario 7). The impact of climate scenarios is greater
377 but better distributed over the whole area (Figure 9C, Scenario A and Figure 9D, Scenario N).
378 For climate change scenario A, water levels in the Northern wetland are lowered by about 50
379 to 60 cm. In the Southern area, the water levels decrease by 25 to 40 cm in the east and by 80
380 to 90 cm in the most elevated part of the modeled area. Generally, wetland areas are more
381 impacted in the Northern catchment, where groundwater levels are also affected by the
382 Baupite peat exploitation. In this catchment, all flooded areas disappear with the worst climate
383 change scenario (scenario N).

384 These results show the possible evolution of the wetland area according to different
385 groundwater abstraction options and climate change scenarios for the end of the century
386 (2081-2100). The wetland area is expected to decrease in any case, and the impact of climate
387 change is stronger than the impact of groundwater abstraction.

388 *4.3 Effect of pumping in the Baupte peat exploitation*

389 One potential solution to save water and mitigate climate and pumping impacts would be to
390 reduce pumping in the Baupte peat exploitation (Figure 8). For all scenarios, stopping all
391 pumping in Baupte would allow a wetland recovery of 4.45 % to 9.19 % of the total area
392 depending on the groundwater abstraction and climate change scenario. Considering the most
393 favorable climate change scenario (Scenario A), the wetland surface area would be
394 approximately equivalent to the current situation, whatever the pumping scenario used (see
395 Figure 8). This effect is apparent in Figure 9E, Scenario 36, where water levels increase by 75
396 to 25 cm in the Sainteny area. For the other scenarios, stopping all pumping in Baupte is not
397 enough to completely balance the loss of wetlands due to climate change. Considering the
398 worst scenario (climate scenario N and Pumping +100 % with existing wells), reduction of
399 the wetlands area would still attain 9.67 %, even if pumping in Baupte is stopped (Figure 9F).

400 **5. Discussion**

401 *5.1 Uncertainty and model limitations*

402 Using numerical models induces some uncertainty that affect the subsequent simulations. This
403 uncertainty may be generated from various possible sources (Refsgaard et al., 2006). Some of
404 them are discussed here below. By adopting a multi-model approach for the climate scenarios,
405 it is possible to incorporate the uncertainty related to the climate models and the uncertainty
406 derived from climate model selection into the assessment of climate change impacts on the

407 Sainteny-Marchésieux catchment. All the 14 climate change scenarios predict a decrease in
408 recharge ranging from 22 to 61 % (Table 3). It results in a decrease of water level and total
409 wetland surface area ranging from 5.3 to 13.6 % (Figure 8), meaning that this decrease is
410 highly probable from this point of view.

411 The accuracy of the predictions will also depends on the quality of the calibration, which
412 varies according to the different variables considered in the study. The volume of drained
413 water presents the major uncertainty because only partial observed stream-discharge data are
414 available. In spite of the lack of data, the 3D hydrogeological model satisfactorily reproduces
415 the measured volumes of drained water with a good correlation ($R^2=0.9$) between simulated
416 and observed values (error less than 5 %). Similarly, the volumes leaving the system by the
417 Baupte boundary condition match the measured quantity of water currently pumped from the
418 peat exploitation. Concerning the hydraulic heads (Figure 5), all residuals are lower than 1m,
419 except for two wells. The model is able to simulate groundwater levels according to different
420 annual climate conditions, even though it slightly over-estimates the hydraulic heads in wet
421 periods and under-estimates them in dry periods, which could also imply that the predicted
422 impacts are slightly overestimated.

423 We here emphasize the relative simplicity of the model, which is focused on the evolution of
424 wetlands extension. Particularly, the use of a seepage boundary condition for the whole
425 modeled surface enables some flexibility regarding the distribution of discharge zones over
426 the domain. These discharge zones are actually variable according to climatic conditions. As
427 an example, low recharge rates induce lower water table and disconnection of river sections,
428 which also implies a decrease of groundwater discharging zones and wetlands areas
429 (Goderniaux et al., 2013). Conceptualizing and representing these processes in the numerical
430 model is crucial to quantify the extents of these wetland areas as a function of recharge.
431 Specifying the locations of rivers and using river boundary conditions appears too restrictive

432 in this case. Although simple, the approach adopted however provides a rapid and easy
433 characterization of wetland extension, which is clear and important parameter for
434 stakeholders.

435 More complex approaches are available for modeling hydrological systems. Integrating more
436 processes into the same model has the advantage of providing more realistic simulations.
437 Indeed it is very useful to have realistic water budget terms. That's why, particularly, fully
438 integrated surface-subsurface models are more and more used (Ebel et al., 2009; Jones et al.,
439 2008; Liggett et al., 2013). However, using more complex hydrological models also involves
440 a large number of parameters, requires important computing times, and makes the calibration
441 step more difficult, so that significant uncertainty may remain from this source. There is a
442 lively debate on the question of the models complexity to be used (Hill, 2006; Hunt and
443 Zheng, 1999). In this study, the model used includes simplifications, which presents some
444 advantages but also some limitations. The processes related to the water transfers in the
445 partially saturated zone are for example not simulated by the hydrological model. The role of
446 these transfers is limited regarding the results of this study because simulations are performed
447 in steady state and the partially saturated zone remains relatively thin. However, for transient
448 simulations, and particularly to evaluate seasonal fluctuations, water transfers in this zone
449 should be further studied. Similarly, the verification of the water budget terms for the GR2M
450 recharge model and the Modflow hydrological model is currently based on annual data. A
451 finer time-discretization would be required to account for seasonality effects. Moreover, more
452 observed data about wetlands extents at the seasonal timescale would also be required. While
453 this study has shown the long term effect of climate change on wetland areas, the implications
454 regarding these seasonal fluctuations remain to be studied and constitute a perspective of this
455 work.

456 *5.2 Groundwater abstraction and climate change scenarios*

457 The groundwater abstraction scenarios were implemented to evaluate the sensitivity of the
458 Cotentin wetlands to future increasing demand. The pumping simulations reflect realistic
459 scenarios of future exploitation, according to local water agencies. In general, pumping in the
460 main aquifer decreases upward fluxes (from the aquifer to the peat) and increases downward
461 fluxes (from the peat to the aquifer). These modifications of water transfer from one
462 compartment to the other may affect water and peat chemistry. Enhanced downward fluxes
463 will actually bring different water, with higher oxygen content and different composition, to
464 the deeper peat layers which may, in turn, affect peat structure, mineralization processes, and
465 water quality. Pumping scenarios which include new extraction wells in the Marchésieux sub-
466 catchment should therefore be preferred to limit environmental impact (see Figure 8 and
467 Figure 9). Although this hydrological basin is less permeable, a similar water volume
468 abstracted (relative to the amount currently extracted at Sainteny) results in a smaller
469 reduction of the wetland water level (Figure 8). Moreover, future increased exploitation
470 should remain below a threshold of 10 to 20 % of the current extracted volume to limit the
471 potential impact on wetland surface area.

472 The 14 climate change scenarios predict a decrease in recharge ranging from 22 to 61 %
473 (Table 3) which results in a decrease of total wetland surface area of 5.3 to 13.6 % (Figure 8).
474 In the long term, the model results clearly show and quantify that the water stresses and the
475 impact on the wetland extents are much greater for the climate change scenarios than for the
476 groundwater abstraction scenarios.

477 Therefore, climate change constitutes a major driver as compared to groundwater exploitation
478 in the modeled area. However, the effects of climate change will be gradually visible over
479 several decades, whereas the other effects are already severe. Furthermore, as all
480 anthropogenic effects are cumulative, the expected impacts of climate change should

481 emphasize the urgent need for mitigation plans. In this context, the modeling results also
482 highlight the effect of the Baupte exploitation on peat water levels. Peat extraction was
483 stopped in 2006. However, local authorities decided to maintain water pumping in order to
484 avoid flooding agricultural fields. In the near future, pumping could be decreased in order to
485 mitigate the impacts of climate change in the Northern Sainteny catchment.

486 Thompson et al. (2009) found similar conclusions regarding climate change impact on a
487 wetland area located in south-eastern England, with significant wetland area decrease by the
488 2050s. The comparison is however difficult as the influence of the groundwater compartment
489 seems less preponderant in their study area. Other studies do not directly calculate wetland
490 extents, but concentrate on groundwater levels and discharge rates evolution. Candela et al.
491 (2009) project decreases in spring discharges to a wetland in Majorca (Spain), for 2025 and 2
492 emission scenarios (A2 and B2). They calculate that a reduction or alternative management of
493 the groundwater abstraction is needed to avoid the partial or complete disappearance of the
494 wetland. Finally, Herrera-Pantoja et al. (2012) calculated significant declining trends in
495 groundwater levels in a wetland located in Eastern England, by the end of the century and
496 using a 'high' greenhouse gases emissions.

497 *5.3 Anthropogenic influences prior to 2012*

498 During the last years, it was often claimed that groundwater extraction was responsible for
499 peatland desiccation and geotechnical damages. To provide a scientific basis to this
500 controversy, the model has been used to analyse the respective effects of anthropogenic
501 activities on groundwater levels over the period 1950-2012. The effects of both the Baupte
502 peatland exploitation and groundwater abstraction were analysed by removing both pumping
503 from the current situation. The effect of climate change was considered by assuming an
504 increase in annual temperature of 1°C from 1950 to 2012, as observed on several climatic
505 stations in the region. The recharge and hydrological models were run with a temperature one

506 degree lower than the current temperature. The results indicated a general decrease in water
507 level, in the investigated zone, between 1950 and 2012. Baupite exploitation and groundwater
508 abstraction had relatively similar impacts ranging from 50 to 85 cm and 35 to 70 cm,
509 respectively. Climate change had a more limited impact of about 20 cm over the last 60 years.

510 The model developed in this study provides interesting insights in the quest to find solutions
511 for this territorial management crisis. It enables the respective impacts of all human activities
512 for the last 60 years to be quantified. The decrease in water-level was reported by local
513 inhabitants, but its extent and the period of occurrence remained unclear. Although the effect
514 of drainage which occurred from the 17th century onwards and more intensively after the
515 Second World War, could not be taken into account, the model results show that more recent
516 human-induced changes have in any case had a major effect during the last decades
517 independently of previous management schemes. Clearly, none of the three anthropogenic
518 effects considered (Baupite exploitation, groundwater exploitation, and climate change) can
519 alone be considered as responsible for peat desiccation. The current state of the peatland
520 appears to result from increasing stress which has several causes. The model results were
521 particularly unexpected for the end-users, who had mainly focused on the impact of
522 groundwater exploitation and had never integrated the potential influence of climate change.
523 This result is particularly important with regard to previous studies which had already
524 indicated severe drawdown (Auterives et al., 2011) and chemical oxidation of the peat
525 (Bougon et al., 2011; De Ridder et al., 2012).

526 **6. Conclusion**

527 The water fluxes occurring between large wetlands and underlying aquifers were analysed by
528 modeling. A simple model was used to simulate groundwater levels, river fluxes through the
529 wetlands and wetland surface extension. The surface flooded is an important parameter for

530 wetland management and special emphasis was given to this variable. It was computed by
531 applying the seepage boundary condition to the entire area modeled, and measuring the water
532 level in the wetland aquifer.

533 The model was used to analyse three different anthropogenic effects: (1) groundwater
534 exploitation in the underlying aquifer, (2) wetland water abstraction in a peat exploitation
535 quarry, and (3) the impact of climate change using data from 14 downscaled climate models.

536 A 100% increase in the groundwater abstraction rate had a maximum impact of 3.7 % on the
537 current wetland surface. Climate change is expected to have a greater impact with potential
538 reduction of the wetland surface area ranging from 5.34 to 13.64 %. Although peat
539 exploitation has ceased, water pumping has been maintained to avoid flooding farmland. The
540 model indicates that the climate change effects could be partly compensated by decreasing
541 and then stopping this pumping.

542 Finally, in order to understand the origin of the geotechnical damage observed in recent years,
543 the model was used to investigate the respective impacts of different anthropogenic activities
544 prior to 2012. Results revealed that during the last 60 years, a wetland water-level decrease of
545 40 to 90 cm could be attributed to the combined impacts of groundwater and peatland water
546 exploitation. It is clearly apparent that all these human activities contribute to lower the peat
547 groundwater level and have already severely destabilized peat functioning. All these activities
548 have to be taken into account in future management strategies which it is urgent to define.
549 Water management will require an appropriate compromise which encompasses ecosystem
550 preservation, economic and public domain activities.

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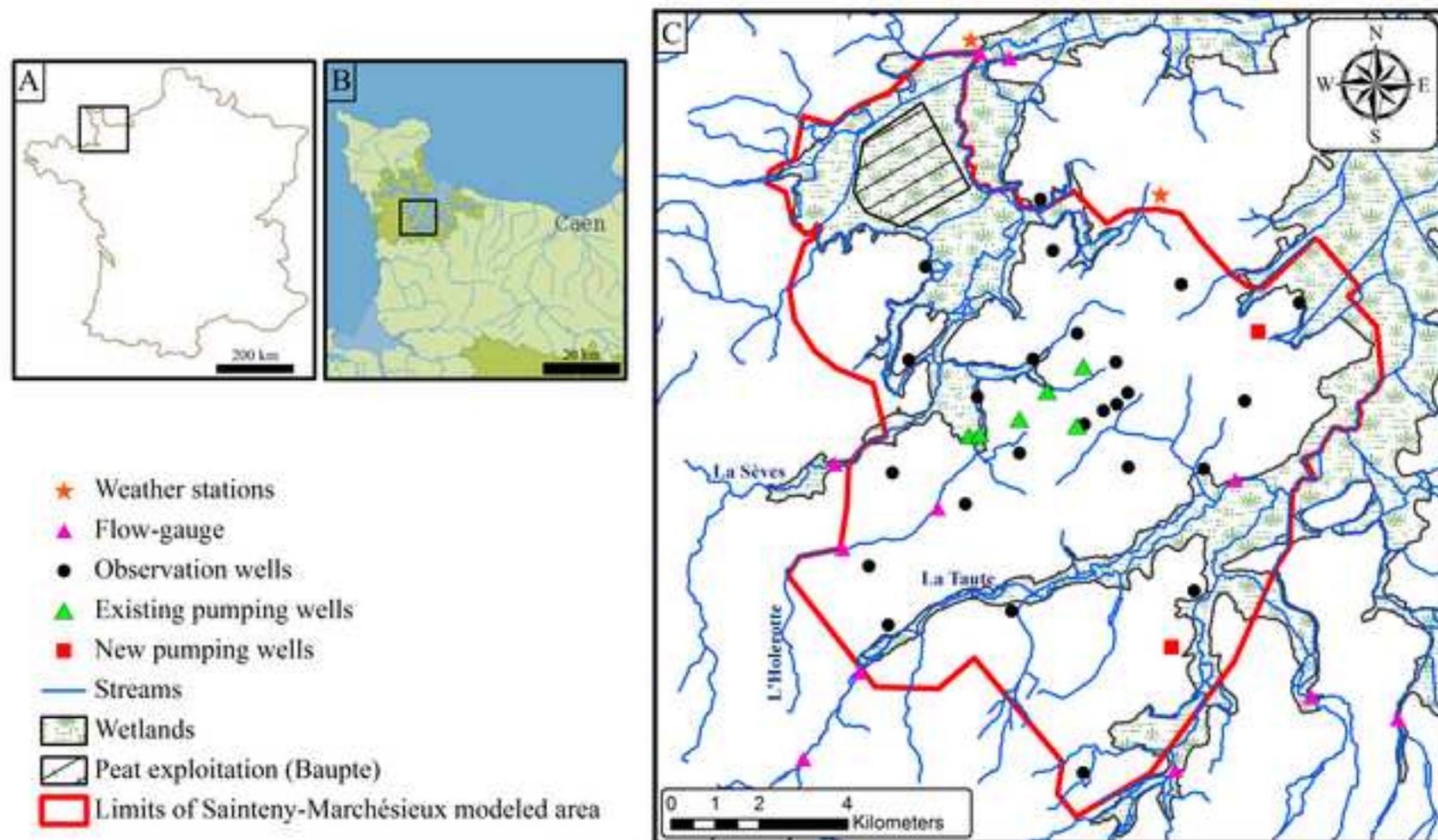
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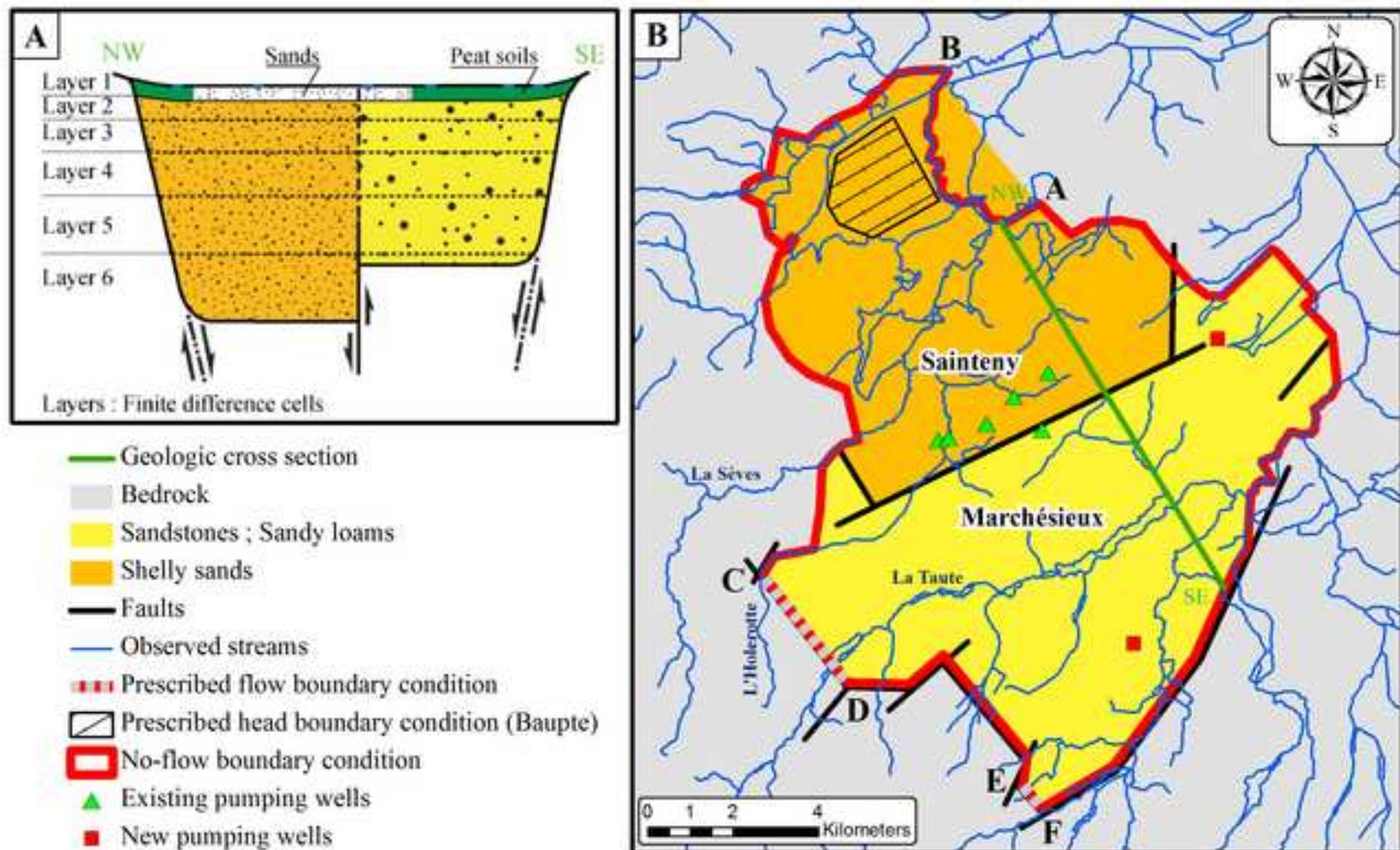
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701 **Tables**702 **Table 1. Calibrated horizontal and vertical hydraulic conductivities**703 **Table 2. Summary of climate change, groundwater abstraction and management scenarios considered in**
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706 **to 3 specific GCMs described in Table 3**707 **Table 3. GCMs used for climate projections, related recharge and percentage of decrease relative to**
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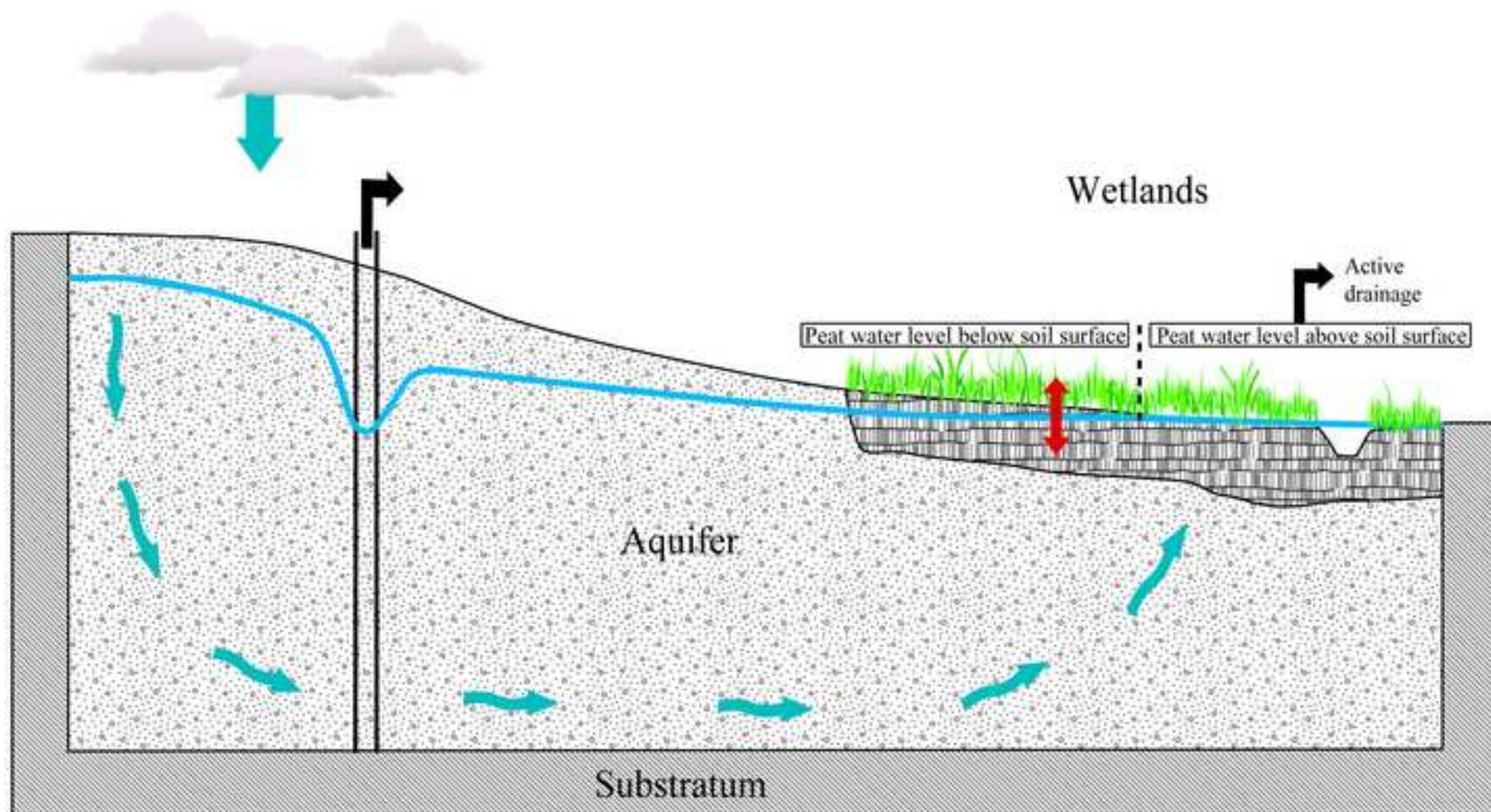
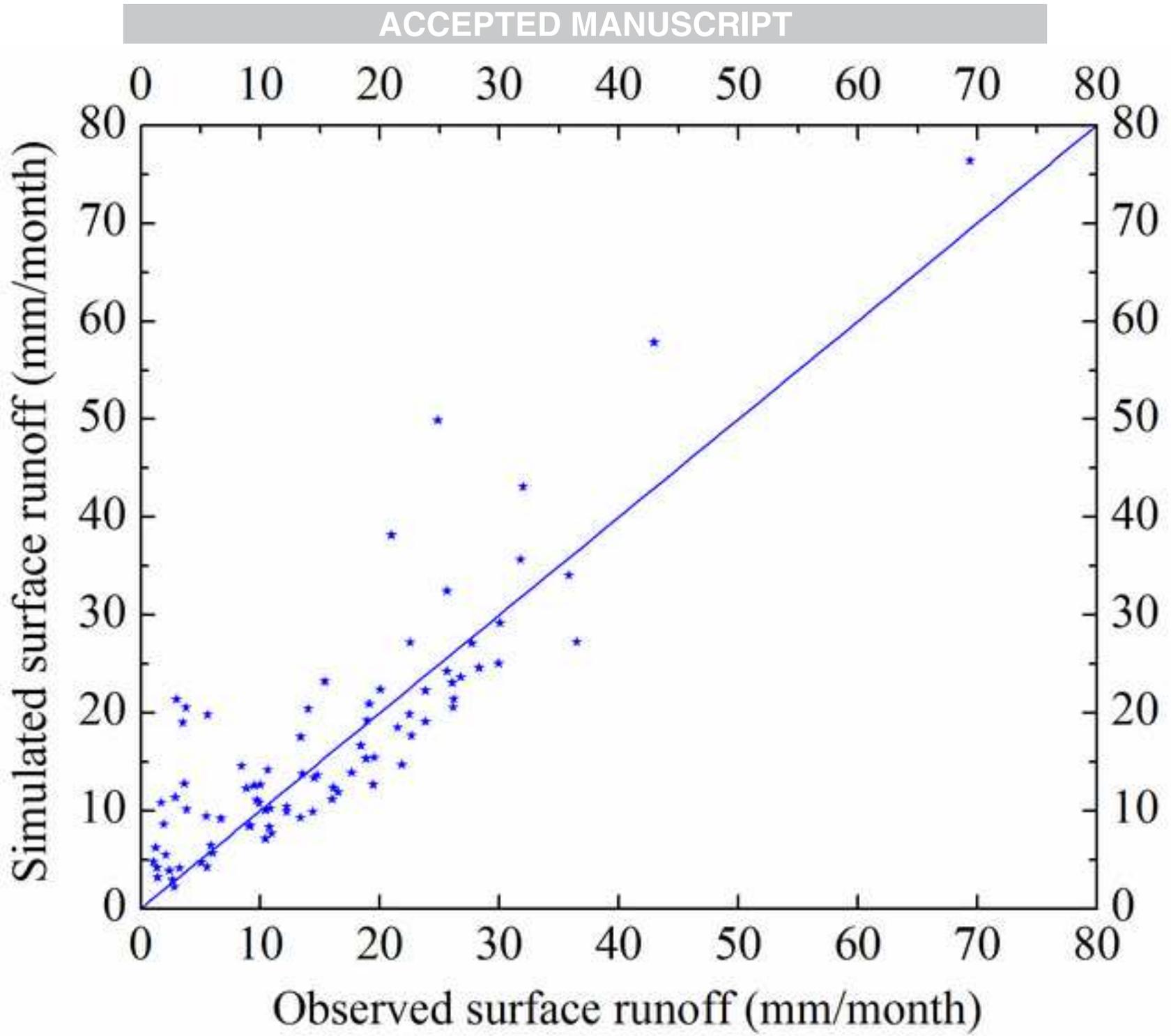
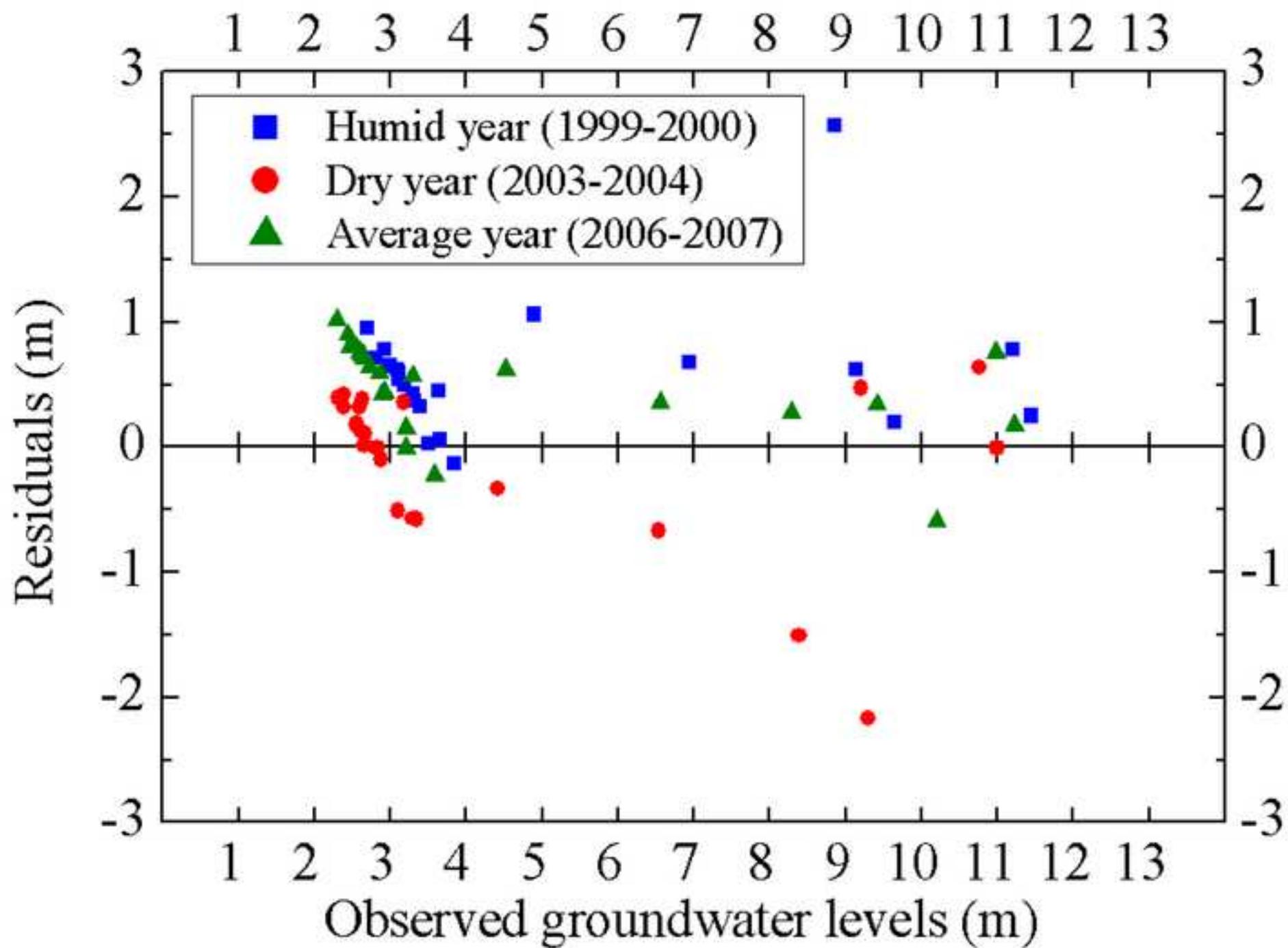


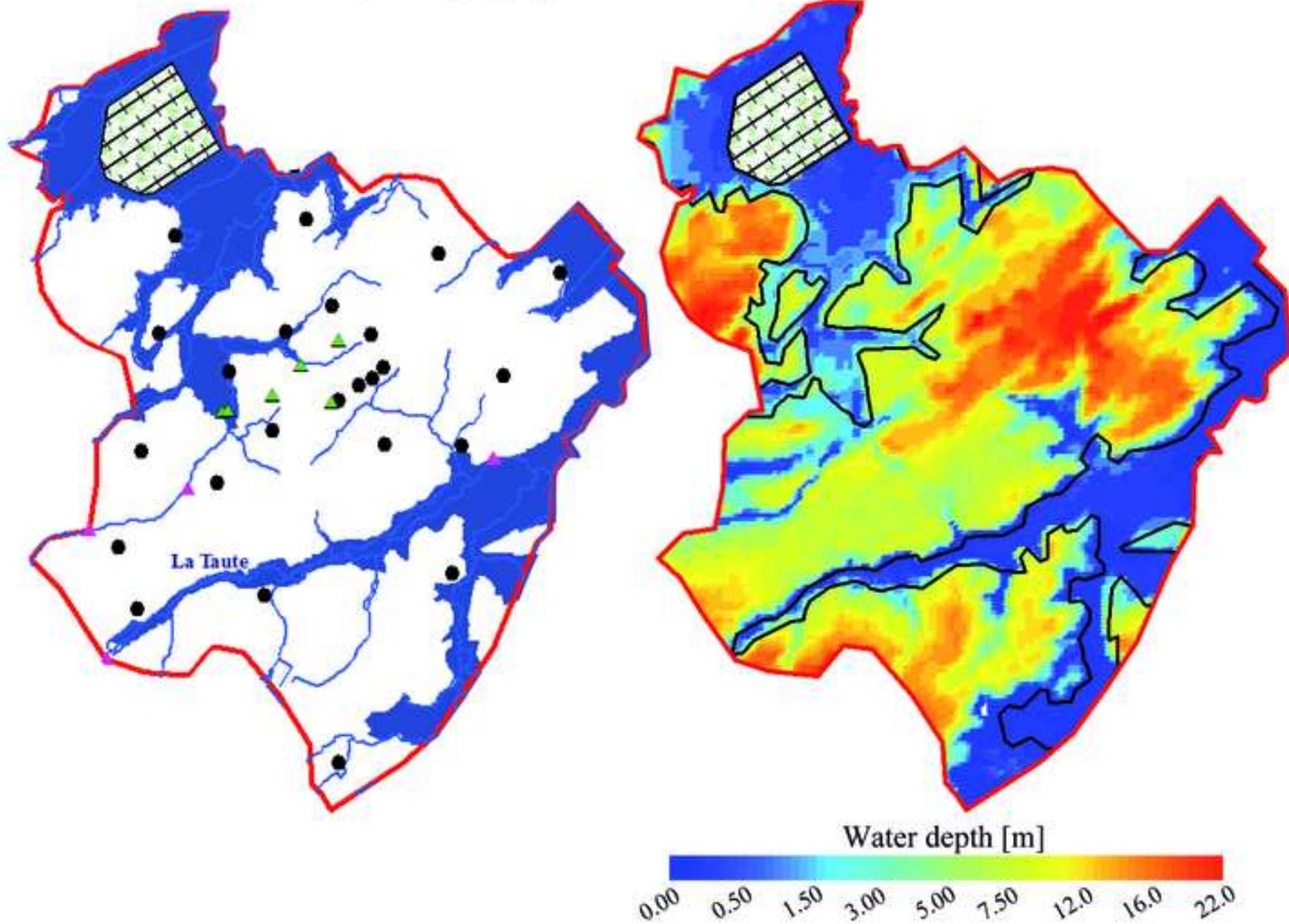
Figure4

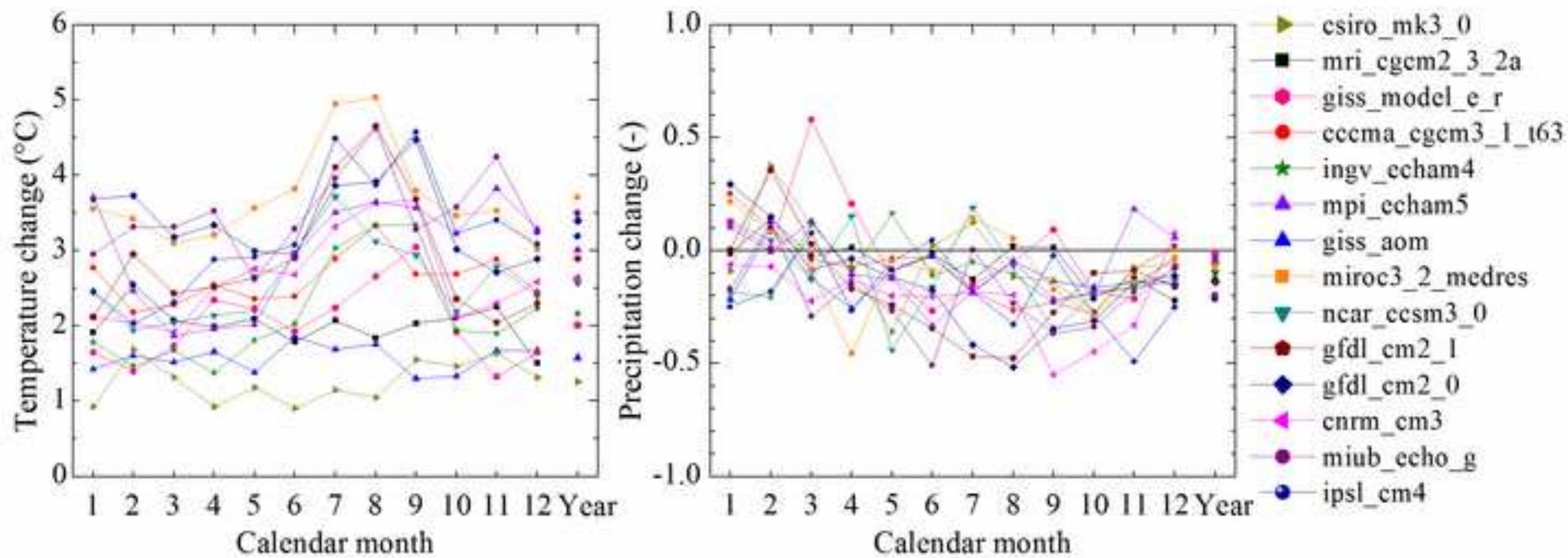


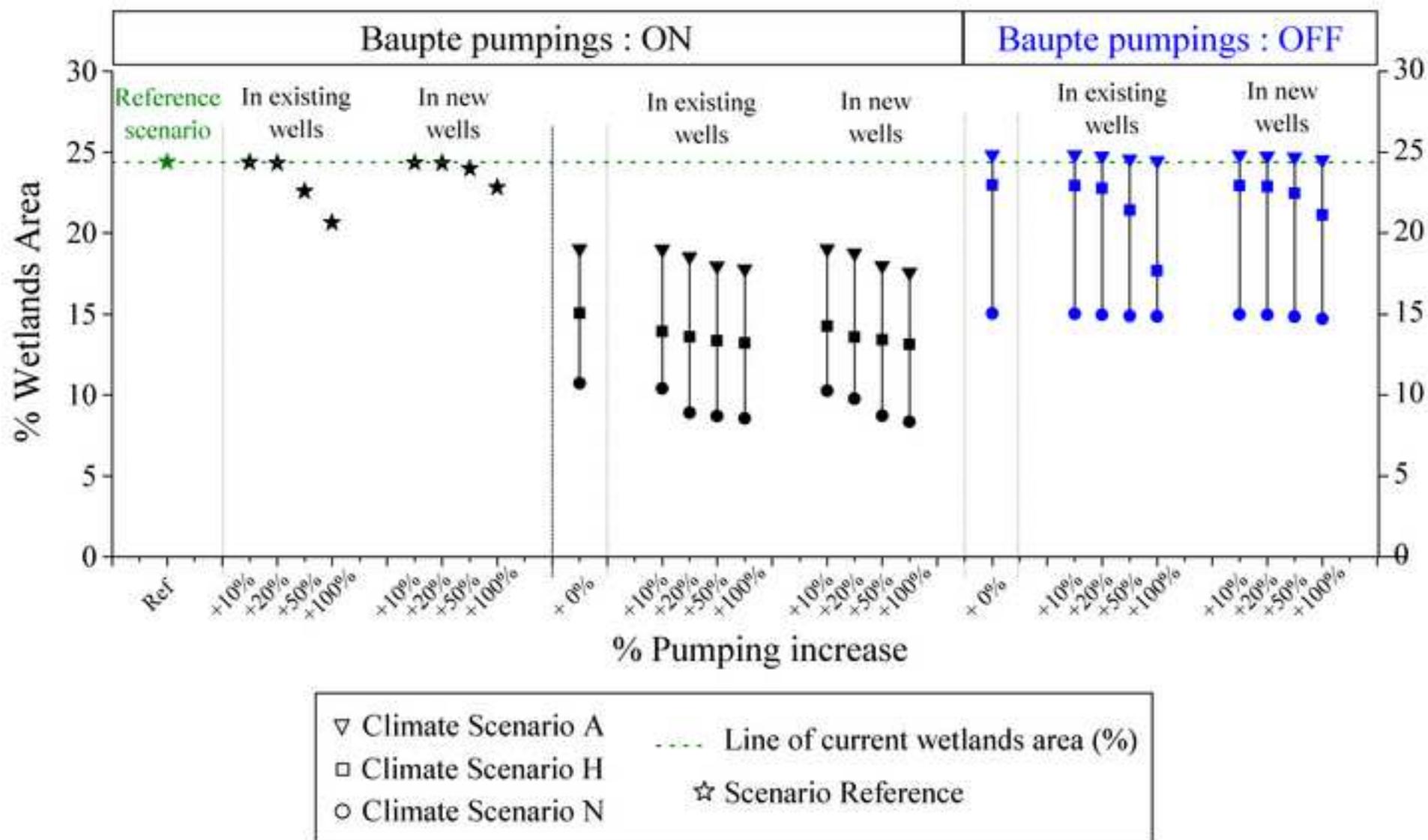


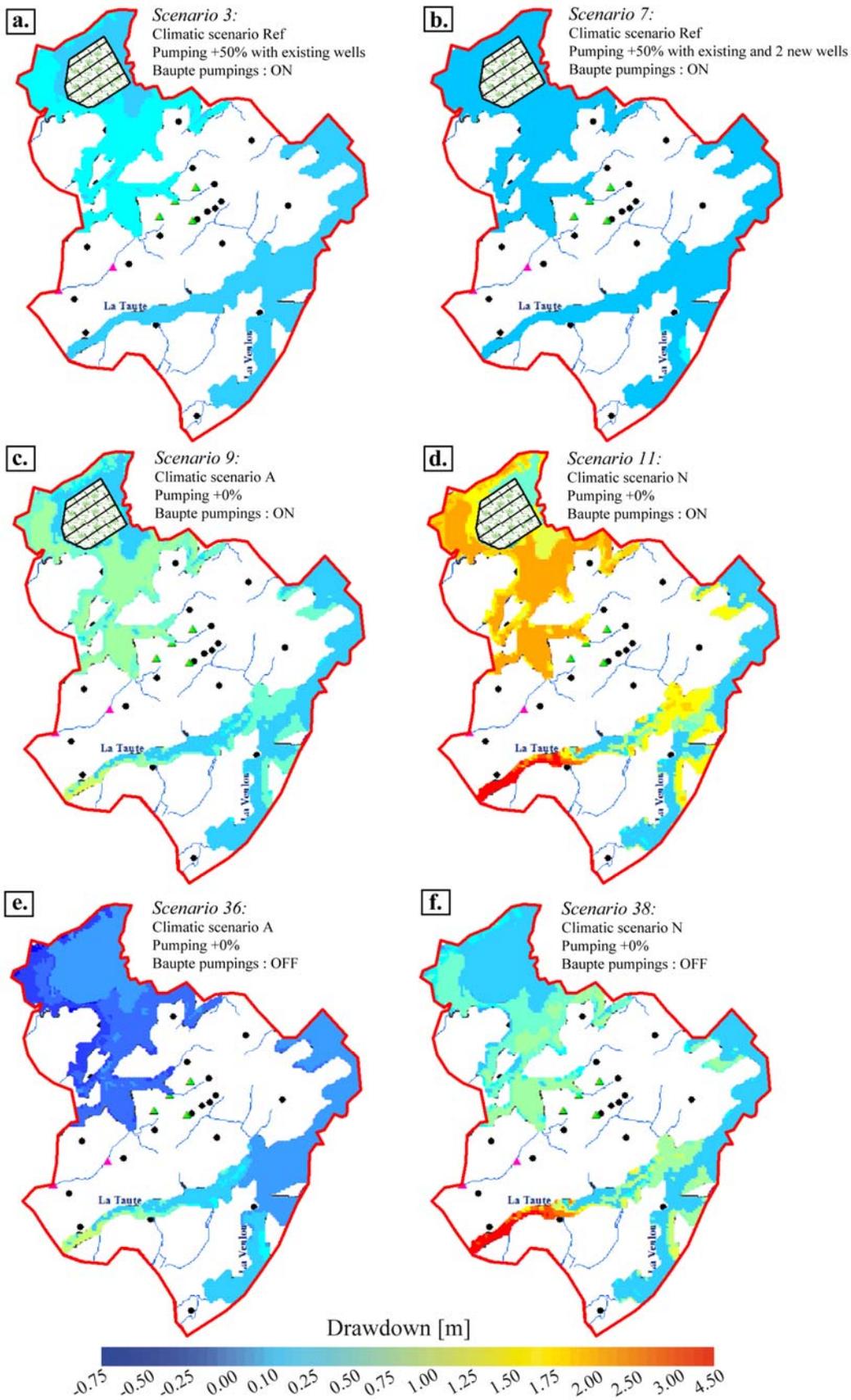
Wetlands observed (Cartography)

Wetlands simulated









Layer	Lithologie	K_{xy} (m/s)	K_z (m/s)
Layer 1	Sands	1×10^{-6}	1×10^{-6}
	Peats	8×10^{-7}	7×10^{-8}
Layer 2, 3, 4, 5 and 6	Shelly sands	8×10^{-3}	8×10^{-3}
	Sandstones	8×10^{-4}	8×10^{-4}
	Sandy loams	5.5×10^{-6}	5.5×10^{-6}
	Sandy loams	2×10^{-5}	2×10^{-5}

Increase of groundwater abstraction	Wells supporting the groundwater abstraction increase	Climatic time slice and GCM				Baupfe pumpings
		1961-2000	2081-2100			
			A	H	N	
0%	Existing	Ref	9	10	11	ON
10%		1	12	13	14	
20%		2	15	16	17	
50%		3	18	19	20	
100%		4	21	22	23	
10%	New	5	24	25	26	
20%		6	27	28	29	
50%		7	30	31	32	
100%		8	33	34	35	
0%	Existing		36	37	38	OFF
10%			39	40	41	
20%			42	43	44	
50%			45	46	47	
100%			48	49	50	
10%	New		51	52	53	
20%			54	55	56	
50%			57	58	59	
100%			60	61	62	

Scenario	Scenario name	Calculated recharge (mm)	Calculated recharge decrease by 2081 – 2100 (%)
Ref	Reference	250	0
A	csri_mk3_0	194	22
B	mri_cgcm3_2a	182	27
C	giss_model_e_r	182	27
D	ccma_cgcm3_1_t63	171	32
E	ingv_echam4	171	32
F	mpi_echam5	171	32
G	giss_aom	163	35
H	miroc3_2_medres	148	41
I	ncar_ccsm3_0	143	43
J	gfdl_cm2_1	137	45
K	gfdl_cm2_0	118	53
L	cnrm_cm3	110	56
M	miub_echo_g	108	57
N	ipsl_cm4	97	61

Climate Scenario		Total influx	Groundwater discharge	Public wells	Baupte
Reference (R=250 mm/yr)	m ³ /yr	5.2E+07	-3.7E+07	-4.9E+06	-1.0E+07
	% of total influx	100	-71.3	-9.4	-19.2
A (R=194 mm/yr)	% of reference total influx	75	-46.9	-9.4	-18.7
H (R=148 mm/yr)		56	-28.7	-9.4	-17.7
N (R=97 mm/yr)		38	-12.1	-9.4	-16.2
A (R=194 mm/yr)	% of total influx	100	-62.6	-12.6	-24.9
H (R=148 mm/yr)		100	-51.4	-16.9	-31.7
N (R=97 mm/yr)		100	-32.1	-25.0	-42.9

726 Highlights

727 ➤ Investigating impacts of climate change and groundwater pumping on wetland extension

728 ➤ Simple model to understand surface-subsurface interaction and wetland vulnerability

729 ➤ Climate change has a greater impact with loss of wetland area by 5.3 to 13.6%

730 ➤ The impact of groundwater abstraction would lead to a maximum decrease of 3.7%

731 ➤ Effects of climate and pumping could be reduced by stop pumping in peat exploitation

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ACCEPTED MANUSCRIPT