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Antoine ARMANDINE LES LANDES[1*], Luc AQUILINA[1], Jo DE RIDDER[1], Laurent LONGUEVERGNE[1], Christian PAGÉ[2], Pascal GODERNIAUX[1,3].

[1]Geosciences 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

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

[3]Geology 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.

1. Introduction

Peatlands are complex and fragile ecosystems driven by many physical, chemical, and biological processes. Numerous studies have provided a comprehensive understanding of wetland hydrology, especially regarding the interactions between surrounding aquifers and surface water networks (Bradley, 2002; Frei et al., 2010; Grapes et al., 2006; Lischeid et al., 2010; Reeve et al., 2000; van Roosmalen et al., 2009; Wilsnack et al., 2001; Winter, 1999). Because peat soils can serve as sinks, sources, and transformers of nutrients and other chemical contaminants, they have a significant impact on water quality, ecosystem productivity and greenhouse gas emissions (Hemond and Benoit, 1988; Johnston, 1991; Kasimir-Klemedtsson et al., 1997; Roulet, 2000). The extent of peatlands is tending to decrease worldwide, (Estimated to 6 % over the period 1993-2007 - Prigent et al. (2012)). However, peatlands are considered as important carbon reserves (15-30 % according to Botch et al. (1995); Turunen et al. (2002)), and important potential sources of CO_2 even though they cover only 3 to 4 % of emerged areas on the earth. As the oxygen concentration in peat increases due to water drawdown, surface decomposition is enhanced by bacterial aerobic processes (Holden et al., 2004). Oxygen enhances organic matter mineralization, leading to CO_2 release to the atmosphere and nutrients production, particularly carbon-bound nitrogen and sulphur. Decreasing groundwater levels can also cause land subsidence, due to the reorganization of the peat structure (Silins and Rothwell, 1998).

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

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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.

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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

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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 m^3 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 m^3 per year. Groundwater abstraction

134   represents approximately 9 % of the total recharge rate.

135   In the north of the catchment, the peatlands in the 'Baupte' 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

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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.

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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 m^3/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 m^3/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

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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.

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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 Baupte peatland (Figure 1)

302   stopped in 2006 but pumping maintained to avoid flooding the surrounding fields which are

303   used for agriculture. An efficient management of Baupte 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 Baupte peat exploitation. This stop is simulated in

307   the model by removing the prescribed head boundary condition over the 0.4 km² 'Baupte'

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

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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

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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 km^2) 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

16

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   Baupte peat exploitation. In this catchment, all flooded areas disappear with the worst climate

383   change scenario (scenario N).

17

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

18

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 (R²=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

19

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

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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

22

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. Baupte 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 (Baupte 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.

551 **Acknowledgements**

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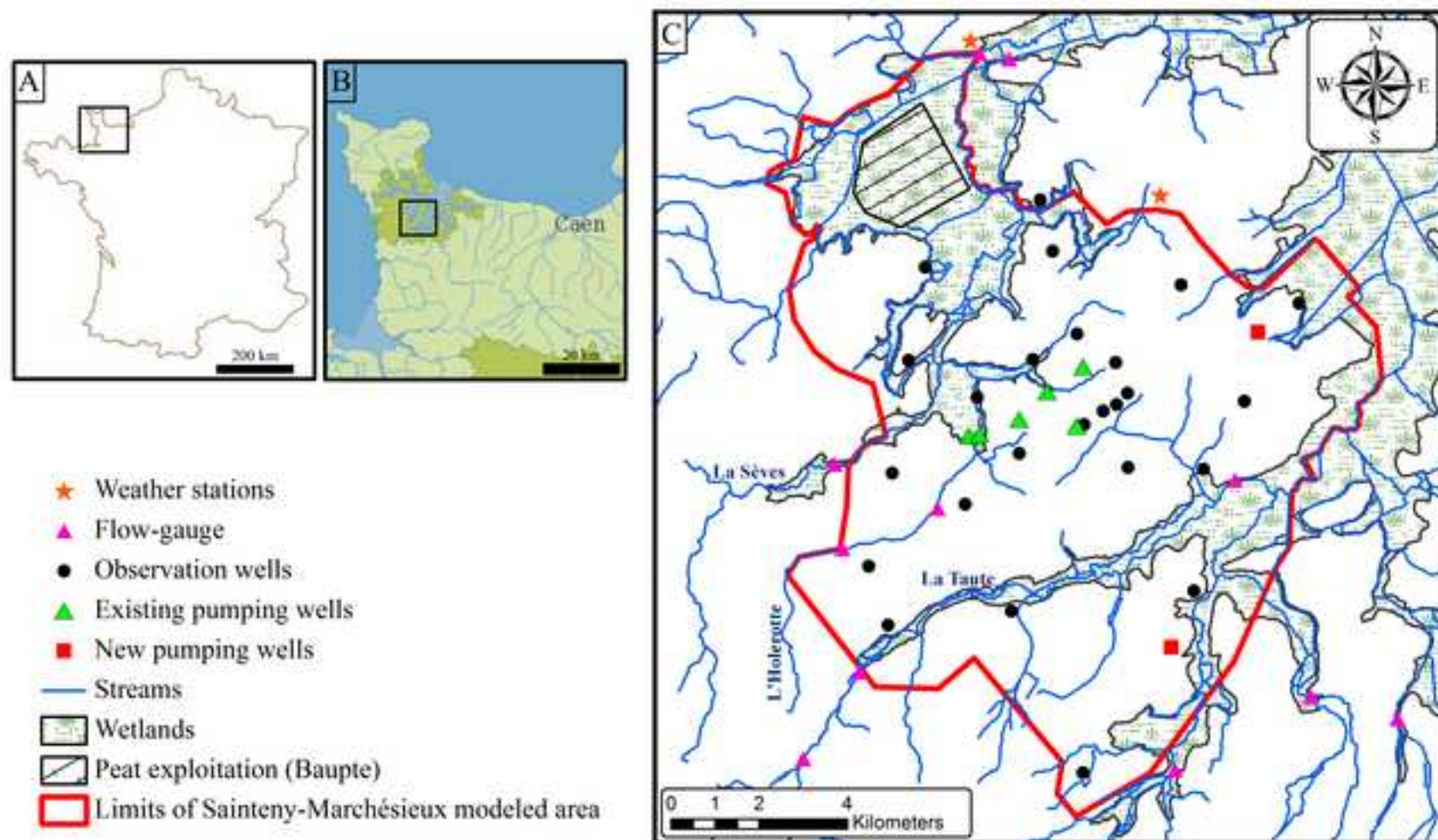629   GroundWater, 44(6): 775-810.

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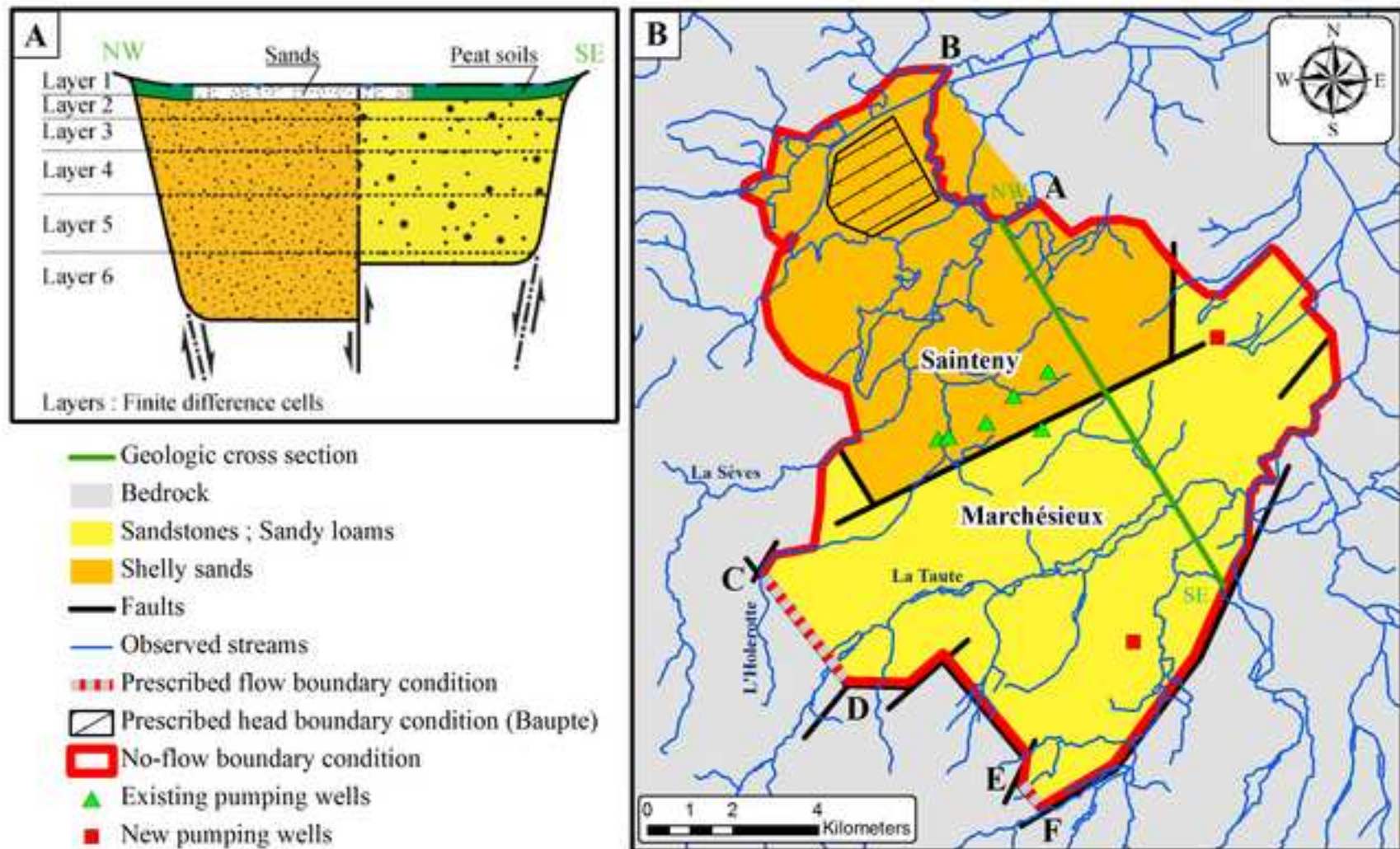667   Journal of Hydrology, 227(1-4): 207-217.

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700

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**
704 **this study. Scenarios are numbered from 1 to 62. The 'Ref' scenario corresponds to no climate change and**
705 **no groundwater abstraction increase. The letters 'A', 'H and 'N' for the time slice 2081-2100 correspond**
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**
708 **current recharge. Climate scenarios A, H and N correspond to the mean and extreme scenarios regarding**
709 **recharge results.**

710 **Table 4. Main water balance terms for the reference and climate change scenarios**

711 **Figures**

712 **Figure 1. Location of the Sainteny-Marchésieux basin. A. Map of France. B. Map of the Cotentin region.**
713 **C. View of the modeled area**

714 **Figure 2. Geology of the Sainteny-Marchésieux basin and boundary conditions of the model. A. Geologic**
715 **cross section. B. Map of boundary conditions of the model**

716 **Figure 3. Conceptual model**

717 **Figure 4. Monthly surface runoff observed and simulated by the modified version of GR2M model.**

718 **Figure 5. Residuals for groundwater levels**

719 **Figure 6. A. Observed mean wetlands area. B. Simulated water table depth over the catchment and**
720 **related limits of the wetlands area (hydrologic year 2006-2007)**

721 **Figure 7. Monthly and annual mean temperature and precipitation changes for the 14 climatic models in**
722 **the Cotentin area. Calendar months are numbered from January to December.**

723 **Figure 8. Percentage of calculated wetlands area in the modeled zone, according to scenarios of**
724 **groundwater abstraction, climate change and management.**

725 **Figure 9. Maps of drawdown for different climate change and management scenarios**

Figure1

ACCEPTED MANUSCRIPT

Weather stations
Flow-gauge
Observation wells
Existing pumping wells
New pumping wells
Streams
Wetlands
Peat exploitation (Baupte)
Limits of Sainteny-Marchésieux modeled area

Figure2

Figure3

Wetlands

Active drainage

Peat water level below soil surface | Peat water level above soil surface

Aquifer

Substratum
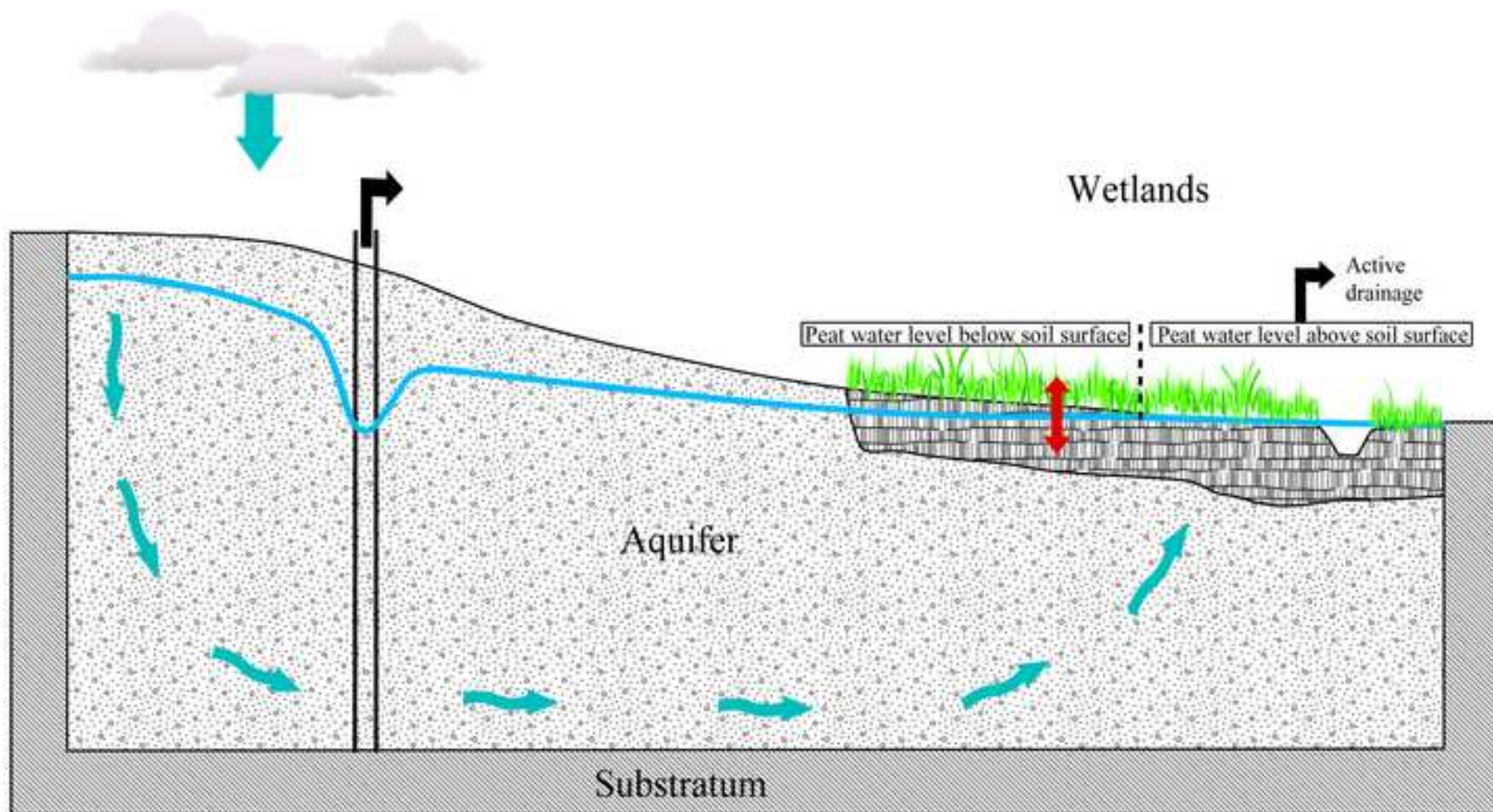
Figure4

Figure5

Figure6

Wetlands observed (Cartography)

Wetlands simulated

Water depth [m]

0.00   0.50   1.50   3.00   5.00   7.50   12.0   16.0   22.0

Figure8

a. *Scenario 3:*
Climatic scenario Ref
Pumping +50% with existing wells
Baupte pumpings : ON

b. *Scenario 7:*
Climatic scenario Ref
Pumping +50% with existing and 2 new wells
Baupte pumpings : ON

c. *Scenario 9:*
Climatic scenario A
Pumping +0%
Baupte pumpings : ON

d. *Scenario 11:*
Climatic scenario N
Pumping +0%
Baupte pumpings : ON

e. *Scenario 36:*
Climatic scenario A
Pumping +0%
Baupte pumpings : OFF

f. *Scenario 38:*
Climatic scenario N
Pumping +0%
Baupte pumpings : OFF

Drawdown [m]

-0.75 -0.50 -0.25 0.00 0.10 0.25 0.50 0.75 1.00 1.25 1.50 1.75 2.00 2.50 3.00 4.50

Table1

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}

Table2

Increase of groundwater abstraction	Wells supporting the groundwater abstraction increase	Climatic time slice and GCM				Baupte 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	

Table3

Scenario	Scenario name	Calculated recharge (mm)	Calculated recharge decrease by 2081 – 2100 (%)
Ref	Reference	250	0
A	**csri_mk3_0**	**194**	**22**
B	mri_cgcm_3_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**

Table4

Climate Scenario		Total influx	Groundwater discharge	Public wells	Baupte
Reference (R=250 mm/yr)	m³/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

732