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Abstract

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

Keywords: Peatlands, groundwater, wetlands, humid zone, climate change, groundwater pumping

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

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

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

2. Study area

2.1. The Cotentin marshes

The Cotentin marshes are located within a large watershed in Normandy (Northwest France, see Figure 1). The study area is situated within a natural reserve, and extends over approximately 135 km². Topography ranges from 0 to 30 m above sea level. Mean annual precipitation and potential evapotranspiration for the period 1946-2010 (from two climatic stations, Figure 1) were 910 mm/yr and 630 mm/yr, respectively. In the lowland areas, the vast wetlands and peatlands partly consist of peat soils and are located along 3 main rivers: the 'Sèves' in the North, the 'Holerotte' in the West, and the 'Taute' in the South (Figure 1). As suggested by hydrologic fluxes and chemical features (Auterives et al., 2011), this wetland area is closely related to groundwater. It is connected with an underlying highly transmissive aquifer and surface-water bodies are integral parts of the groundwater flow systems. For several centuries, this large wetland has undergone numerous disturbances. In the 18th century the wetland was flooded 9 months per year (Bouillon-Launay, 1992). Since 1712, a human-controlled drainage system has gradually been set up. From 1950 until now, the flooding season has been reduced to only 3 months on average due to agricultural constraints. The top peat profile is thus subjected to longer periods of desiccation. Beside agricultural pressure, the underlying aquifer is also used as a drinking water supply, since 1992. Due to an increasing demand for high-quality water, the authorities plan to increase groundwater abstraction in the near future. The Cotentin peatlands are nevertheless also classified as a natural reserve for specific wildlife and plant species. Additionally, geotechnical perturbations such as the collapse of parts of houses or fissures in constructed walls have also been reported along the border of the peatland. These perturbations have generated public manifestations, and the filing of legal claims in early 2012. It was often claimed during these manifestations that groundwater extraction was responsible for the observed damage. As a consequence, the Cotentin marshes are at the centre of different interests, which must be integrated by stakeholders into their management plans: ecological activities through the preservation of wetlands, economic activities through the preservation of farmland, and public domain activities through the distribution of drinking water.

2.2. The Sainteny-Marchésieux aquifer

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

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

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

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

3. Modeling

3.1 Model implementation

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

- Sections B-C, D-E and F-A correspond to the interface between bedrock and sediments inside the graben. According to the geology and measured groundwater levels, this interface is considered as impermeable. A no-flow boundary condition is prescribed along these sections.
- Section A-B corresponds to a stream section, which is considered as a main drainage divide. A no-flow boundary condition is implemented along this stream section.
- Sections C-D and E-F also correspond to the graben limits but measured groundwater levels show that groundwater fluxes, from the adjacent geological formation, feed the aquifer. Along these sections, a groundwater flux, equal to the recharge rates times the upstream areas, is prescribed.

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

3.2 Model Discretization

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

3.3 System stresses

Recharge and wells pumping rates are applied as input to the model. Pumping rates are calculated from the abstracted groundwater volumes, which have been collected for years by the regional water agencies. Recharge values are applied on the whole modeled area. They are computed externally using a water balance method, based on a modified version of the parsimonious monthly lumped model GR2M (Mouelhi et al., 2006). The GR2M model obtained one of the best performances in a benchmark test of 410 basins throughout the world in different climatic contexts, as compared to 9 other models with generally more parameters (Mouelhi et al., 2006). The GR2M model has been designed to separate rainfall into actual evapotranspiration, surface runoff and transfer to the routing store, which is interpreted here as aquifer recharge (see model description at http://www.cemagref.fr/webgr/IndexGB.htm). Observed rainfall and potential evapotranspiration, provided by 'Meteo France', are used as GR2M inputs. The GR2M model is calibrated to monthly surface runoff data, which are calculated by baseflow separation from measured river flow rate time series. Data are available over a time frame ranging from January 1999 to December 2000 and January 2003 to December 2007 and includes both wet (1999-2000) and very dry years (2003-2004), which maximizes the descriptive ability of the model over a large interval of climatic fluctuations. This is particularly important in the context of future climate change where applied stresses typically go beyond the calibration interval. The calibration is limited to a 1-parameter calibration process, which is here the soil storage capacity, and carried out on the square root of surface runoff to allow equal weight to high and low flow situations (Oudin et al., 2006). In the optimization process, the Nash-Sutcliffe criterion (Nash and Sutcliffe, 1970) was used as the objective function, and supplemented with the constraint to conserve the total amount of surface runoff ($\sum Q_{obs} / \sum Q_{sim} = 1$), where Q_{sim} and Q_{obs} are simulated and observed surface runoff (Figure 4). The Nash-Sutcliffe criterion is 0.70 and the calculated annual recharge ranges from 164 mm/yr to 338 mm/yr. On an annual basis, the total amount of water in rivers is also preserved. The sum of simulated surface runoff and recharge is very close to the observed flow rate in rivers. For the wet (1999-2000) and dry (2003-2004) years, the error is equal to 2 and 4 %, respectively. Checking this relation prevents under or overestimation of calculated annual recharge due to errors on the actual evapotranspiration term. This calibrated 'GR2M' mass-balance model is subsequently used to externally calculate the recharge to be applied as input to the hydrological Modflow model, for historic and future climatic scenarios (see Section 3.5).

3.4 Calibration and validation of the hydrological model

The hydrological Modflow model was calibrated to the observed *i)* aquifer hydraulic heads, *ii)* spatial distribution of wetland area and *iii) stream base-flow*. The calibration was performed in steady state conditions for two humid and dry contrasted years, 1999-2000 (R=338 mm/yr) and 2003-2004 (R=164 mm/yr), respectively, for which daily climatic data were available. The calibration was performed automatically using the PEST module coupled with Modflow, and by adjusting the hydraulic conductivities of the different geological formations within specific ranges provided by field tests (Auterives, 2007; Auterives et al., 2011). This calibration was validated using data from the hydrologic year 2006-2007 (R=263 mm/yr), which is close to the 1961-2000 average precipitation and temperature statistics (where R=250 mm/yr). Results of the calibration are shown in Table 1, Figure 5 and Figure 6, for hydraulic conductivities, groundwater levels and wetland surface, respectively. Table 1 shows the calibrated hydraulic conductivities of the geological formations represented in the model. The seepage conductance is set to a high value, calculated from a hydraulic conductivity which is significantly higher than the hydraulic conductivity of the geological layers. Figure 5 presents residuals for the groundwater levels, calculated as the difference between the observed and simulated values. Figure 6 shows the observed and simulated wetland areas. The "observed wetland areas" are given by cartographic data (data base from the local conservatory park: "Parc Naturel des marais du Cotentin et du Bessin") which are representative of the mean climatic conditions of the time period 1961-2000. These wetlands are defined as zones where a groundwater level close to the soil surface is maintained during a large part of the year. The "simulated wetland areas" are calculated from the model outputs. A finite difference cell is considered as part of the wetland area when the simulated groundwater level is less than 0.5 m below the ground surface. Observed groundwater discharge volumes are calculated as the difference between the main stream inlets (Sèves, Holerotte and Taute) and outlets (Sèves and Taute) volumes, where gauging stations are located (Figure 1). The errors between observed and simulated volumes of groundwater drained from the aquifer to the surface domain (through the seepage boundary condition) are below 5 %. The volume of water extracted by the prescribed head boundary condition is equivalent to the quantity of water pumped by the Baupte peatland manager: approximately 10 million m^3 each year.

3.5 Future scenarios

Future scenarios for groundwater abstraction and climate change were applied as input to the calibrated model, to assess their respective impacts on the catchment, with particular focus on wetland extension. These scenarios are compared with a reference simulation corresponding to the average recharge and groundwater abstraction for the period 1961-2000. The reference recharge is 250 mm/yr and the abstracted groundwater volumes are 5 million m^3/yr. The climate change, groundwater abstraction and management scenarios considered in this study are summarized in Table 2.

3.5.1 Future groundwater abstraction

Groundwater abstraction volumes that will be required in the future are defined from projections made by the local water agency. Four different scenarios are tested, considering an increase in groundwater demand of 10 %, 20 %, 50 % and 100 %, relative to the current volumes (5 million m^3/yr) (Table 2). Two different management plans are considered and tested with the model. The first plan consists in applying the increase in groundwater demand to the pumping rates of the 6 existing wells currently used (Figure 1) (Scenarios 1 to 4 in Table 2). The second plan consists in using two new wells located in the Marchésieux aquifer (Figure 1) to support the increase in groundwater demand (Scenarios 5 to 8). In this second plan, the abstraction flow rates in the existing wells are kept constant.

3.5.2 Climate change

Climate change impact studies cannot directly use the output of global climate models (GCM) because of discrepancies between the extent of the impact model (135 km²) and the horizontal resolution of these numerical models (~250 km, see Solomon et al. (2007)). Downscaling methodologies are commonly used to overcome this problem. Such methods are either dynamically and/or statistically based. In the current study, DSCLIM, a statistical downscaling methodology developed at CERFACS was applied to work at an 8 km resolution. This method is based on the physical relationship between large-scale atmospheric circulations and the local-scale climate (Boé et al., 2009; Fowler et al., 2007b; Pagé et al., 2009). Although downscaling methods are also a source of uncertainty (Fowler et al., 2007a), we chose to focus on climate model uncertainty, which has been shown to be conservative for hydrological impact studies in the French context (Ducharne et al., 2009). This was applied to produce climate scenarios for specific chosen locations in France. Using this methodology, 14 GCMs were downscaled from the 2007 CMIP3 database for the A1B greenhouse gas (GHG) scenario over the periods 1961-2000 and 2081-2100, as shown in Table 3 (see Solomon et al., 2007, for details about the GCMs). Scenario A1B is a sub-category of storyline A1. The A1B scenario was selected because of the availability of several A1B downscaled scenarios, which make possible the evaluation of uncertainties.

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

3.5.3 Coupling climate change, groundwater abstraction and management

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

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

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

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

4. Results

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

4.1 . Wetland surface reduction

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

Simulations of the impacts of climate change indicate a significant reduction of wetland surface area by the end of the century (2081-2100), which is correlated to the decrease of recharge (ranging from -22 % to -61 %, see Table 3). Considering unchanged groundwater abstraction, reduction of the wetland surface area ranges from -13.64 % (18.4 km^2) for the worst climatic scenario N (recharge of 97 mm) to -5.34 % (7.2 km^2) for the most favorable scenario A (recharge of 194 mm). These results also provide important information about the respective influence of groundwater abstraction and future climate change. On the scale of the modeled area as a whole, climate change generally induces a larger reduction in wetland area, than any of the groundwater abstraction scenarios. Although scenario A is the most "favorable" climatic scenario, the impact on wetland surface area is actually more important than the worst groundwater abstraction scenario. As shown in Figure 8, the combined impact of climate change and groundwater abstraction is even more important and ranges from -5.36 % to -16.04 %, depending on the climate change scenario and location of the pumping wells.

Regarding water balance terms, fluxes entering the domain correspond to the recharge applied on the top cells and groundwater entering by specified flux boundary condition (See Section 3.1). These specified groundwater fluxes represent 36 % of total water influx in the modeled domain. Fluxes leaving the domain correspond to the groundwater discharge, pumpings in the public water distribution wells and pumpings in the Baupte peat exploitation. For the reference scenario, these terms correspond to 72 %, 9 % and 19 % of total influx, respectively. Numerical simulations allow quantifying the absolute and relative evolution of these terms considering various stresses (Table 4). For climate change scenarios with unchanged groundwater abstraction, absolute values of all terms logically decrease with recharge and more extreme climate change. However, the proportion of abstracted groundwater (public wells and Baupte) relatively to total influx increases to the detriment of groundwater discharge. For the worst climate change scenario (scenario N), groundwater discharge is only 32.1 % of total influx. In cubic meters, this represents a decrease of more than 80 % compared to the reference simulation. Finally, Table 4 also shows that the decrease of total water influx in climate change scenarios is greater than groundwater abstraction by public wells, which partly explains the preponderant impact of climate change on wetland areas. Relations between input stresses and hydrogeology variables are however complex and dependent on many parameters (such as geology, topography, locations of pumping wells), so that numerical modeling is required for an objective impact quantification.

4.2 Wetland spatial distribution

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

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

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

4.3 Effect of pumping in the Baupte peat exploitation

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

5. Discussion

5.1 Uncertainty and model limitations

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

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

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

We here emphasize the relative simplicity of the model, which is focused on the evolution of wetlands extension. Particularly, the use of a seepage boundary condition for the whole modeled surface enables some flexibility regarding the distribution of discharge zones over the domain. These discharge zones are actually variable according to climatic conditions. As an example, low recharge rates induce lower water table and disconnection of river sections, which also implies a decrease of groundwater discharging zones and wetlands areas (Goderniaux et al., 2013). Conceptualizing and representing these processes in the numerical model is crucial to quantify the extents of these wetland areas as a function of recharge. Specifying the locations of rivers and using river boundary conditions appears too restrictive in this case. Although simple, the approach adopted however provides a rapid and easy characterization of wetland extension, which is clear and important parameter for stakeholders.

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

5.2 Groundwater abstraction and climate change scenarios

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

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

Therefore, climate change constitutes a major driver as compared to groundwater exploitation in the modeled area. However, the effects of climate change will be gradually visible over several decades, whereas the other effects are already severe. Furthermore, as all anthropogenic effects are cumulative, the expected impacts of climate change should emphasize the urgent need for mitigation plans. In this context, the modeling results also highlight the effect of the Baupte exploitation on peat water levels. Peat extraction was stopped in 2006. However, local authorities decided to maintain water pumping in order to avoid flooding agricultural fields. In the near future, pumping could be decreased in order to mitigate the impacts of climate change in the Northern Sainteny catchment.

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

5.3 Anthropogenic influences prior to 2012

During the last years, it was often claimed that groundwater extraction was responsible for peatland desiccation and geotechnical damages. To provide a scientific basis to this controversy, the model has been used to analyse the respective effects of anthropogenic activities on groundwater levels over the period 1950-2012. The effects of both the Baupte peatland exploitation and groundwater abstraction were analysed by removing both pumping from the current situation. The effect of climate change was considered by assuming an increase in annual temperature of 1°C from 1950 to 2012, as observed on several climatic stations in the region. The recharge and hydrological models were run with a temperature one degree lower than the current temperature. The results indicated a general decrease in water level, in the investigated zone, between 1950 and 2012. Baupte exploitation and groundwater abstraction had relatively similar impacts ranging from 50 to 85 cm and 35 to 70 cm, respectively. Climate change had a more limited impact of about 20 cm over the last 60 years.

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

6. Conclusion

The water fluxes occurring between large wetlands and underlying aquifers were analysed by modeling. A simple model was used to simulate groundwater levels, river fluxes through the wetlands and wetland surface extension. The surface flooded is an important parameter for wetland management and special emphasis was given to this variable. It was computed by applying the seepage boundary condition to the entire area modeled, and measuring the water level in the wetland aquifer.

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

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

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

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Tables

Table 1. Calibrated horizontal and vertical hydraulic conductivities

Table 2. Summary of climate change, groundwater abstraction and management scenarios considered in this study. Scenarios are numbered from 1 to 62. The ‘Ref’ scenario corresponds to no climate change and no groundwater abstraction increase. The letters ‘A’, ‘H and ‘N’ for the time slice 2081-2100 correspond to 3 specific GCMs described in Table 3

Table 3. GCMs used for climate projections, related recharge and percentage of decrease relative to current recharge. Climate scenarios A, H and N correspond to the mean and extreme scenarios regarding recharge results.

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

Figures

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

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

Figure 3. Conceptual model

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

Figure 5. Residuals for groundwater levels

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

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

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

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

Figure1

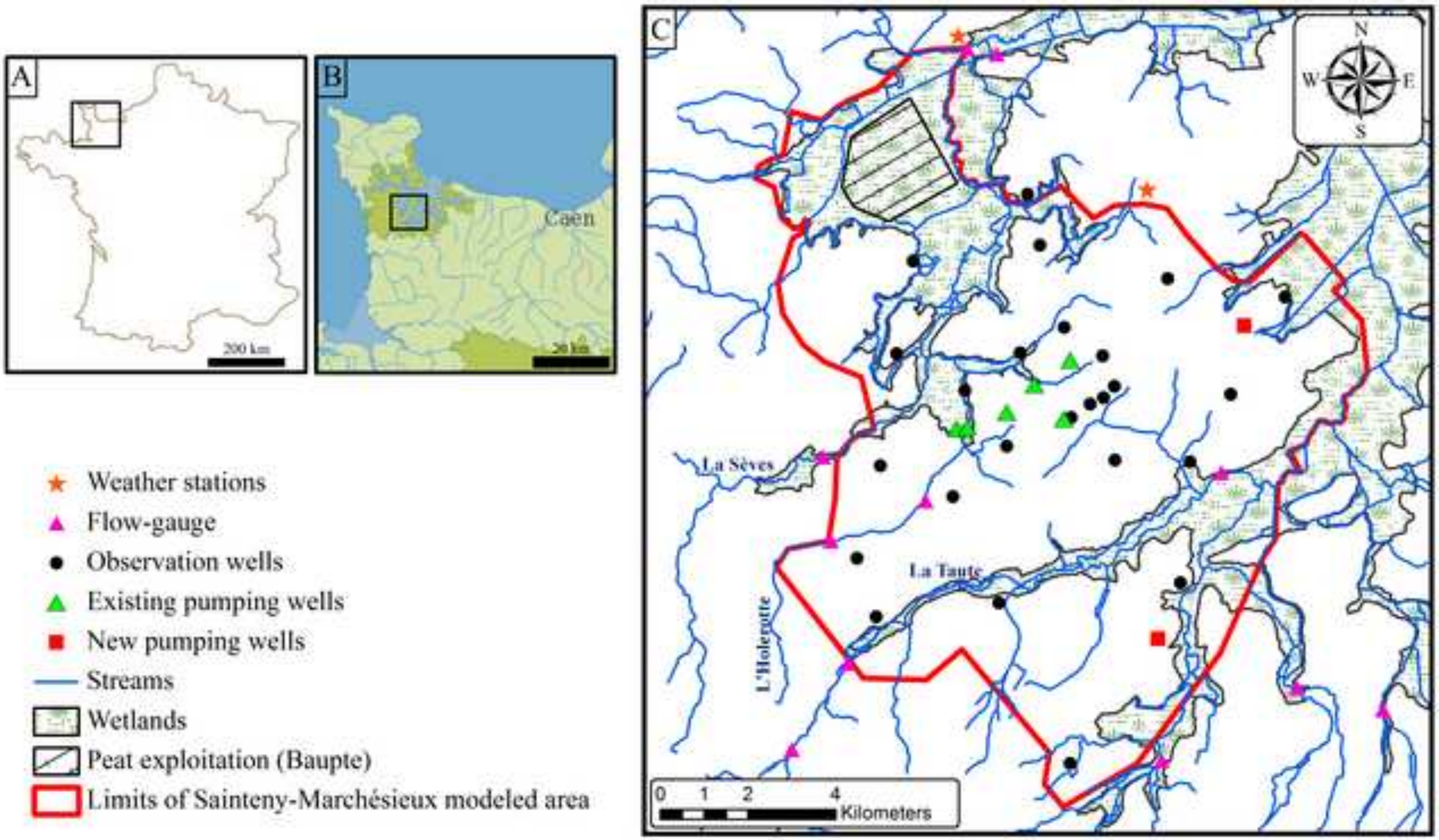

A
200 km
B
Caen
20 km
C
N
W
E
S
La Sèves
La Taute
L'Holerotte
0 1 2 4 Kilometers
Weather stations
Flow-gauge
Observation wells
Existing pumping wells
New pumping wells
Streams
Wetlands
Peat exploitation (Baupte)
Limits of Sainteny-Marchésieux modeled area

Figure2

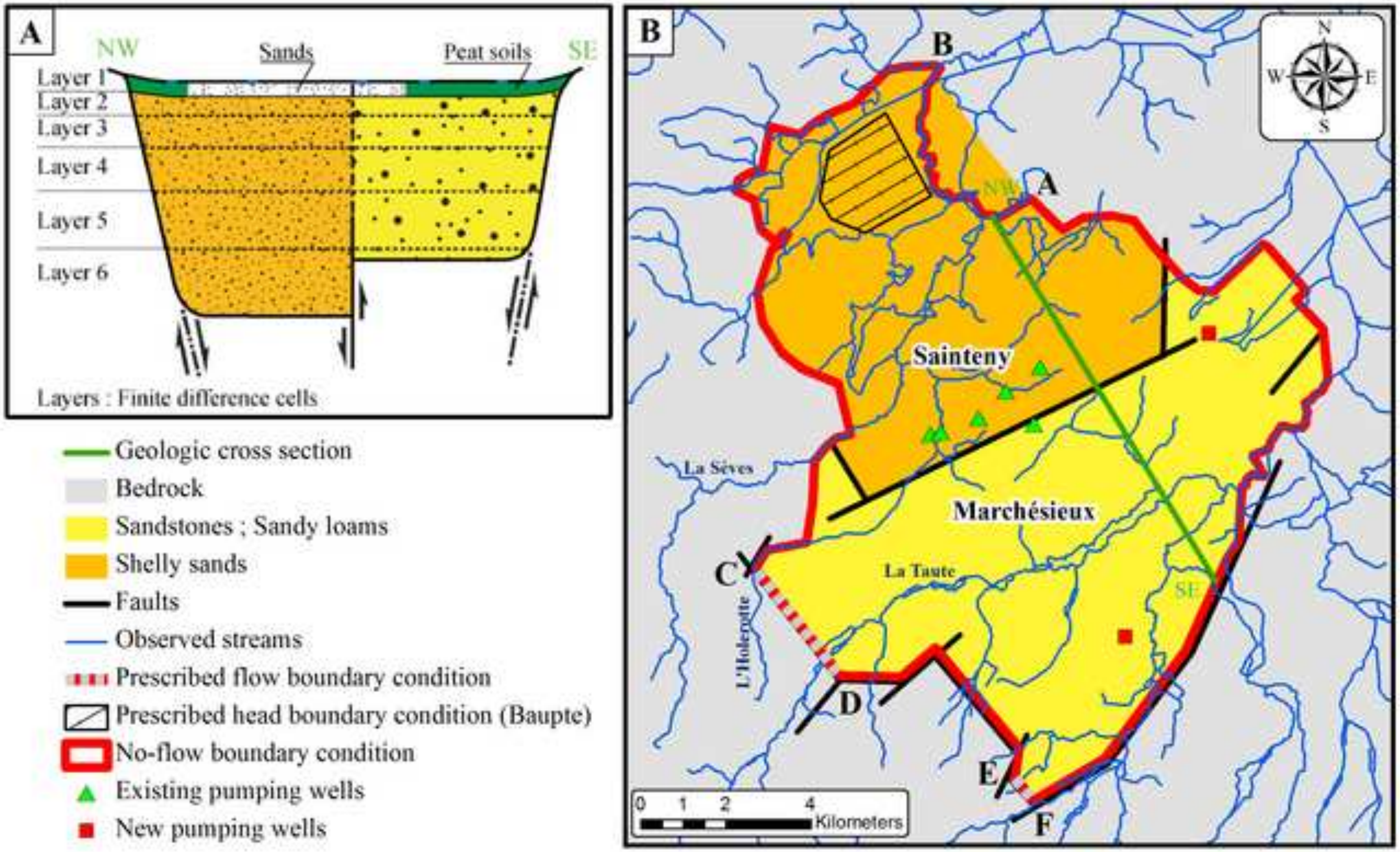

A
NW
Sands
Peat soils
SE
Layer 1
Layer 2
Layer 3
Layer 4
Layer 5
Layer 6
Layers : Finite difference cells
Geologic cross section
Bedrock
Sandstones ; Sandy loams
Shelly sands
Faults
Observed streams
Prescribed flow boundary condition
Prescribed head boundary condition (Baupte)
No-flow boundary condition
Existing pumping wells
New pumping wells
B
N
W
E
S
NW
A
Sainteny
La Sèves
Marchésieux
C
La Taute
SE
L'Holerotte
D
E
F
0 1 2 4
Kilometers

Figure3

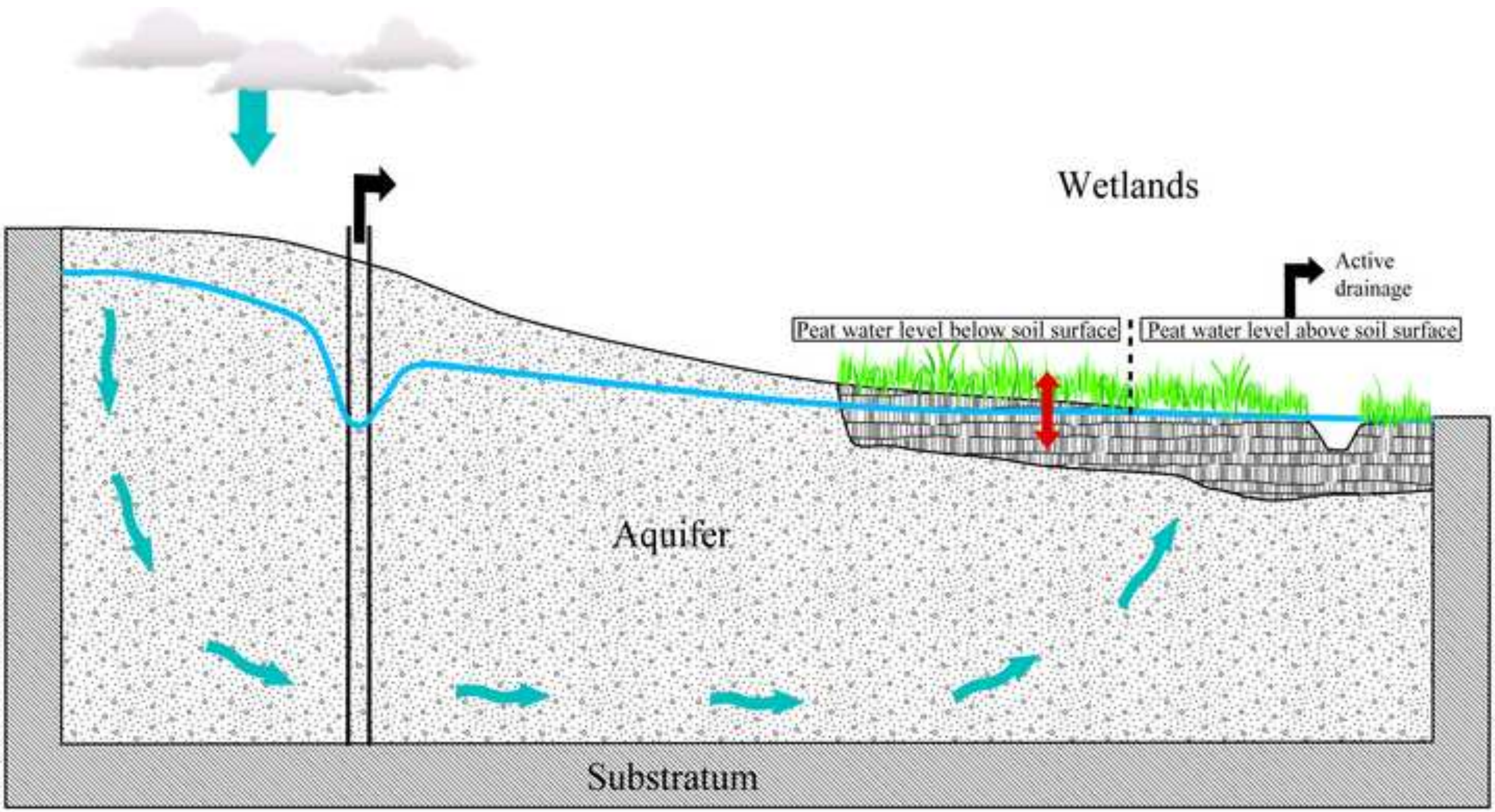
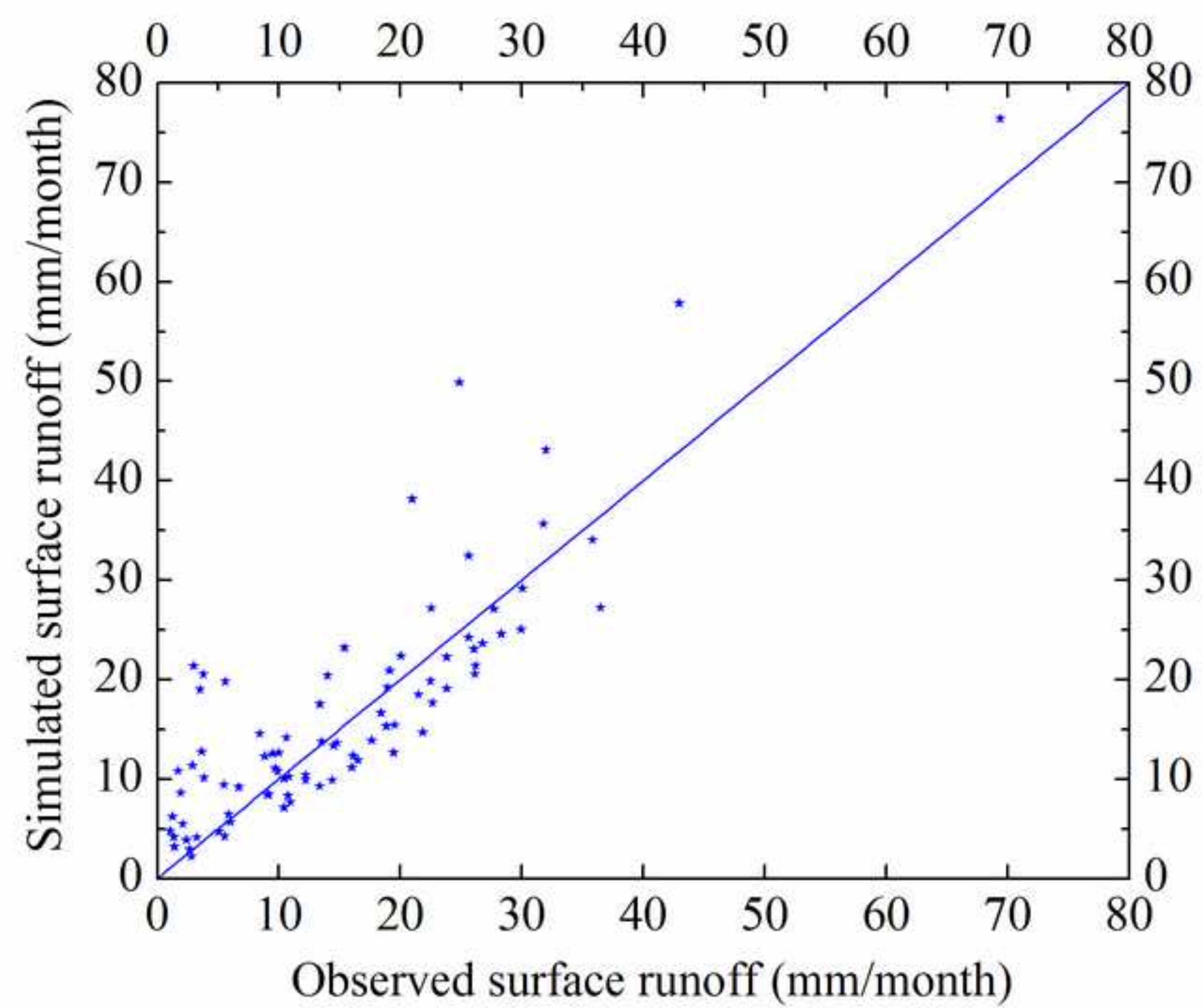

Wetlands
Active
drainage
Peat water level below soil surface
Peat water level above soil surface
Aquifer
Substratum

Figure4



0
10
20
30
40
50
60
70
80
Simulated surface runoff (mm/month)
Observed surface runoff (mm/month)

Figure5

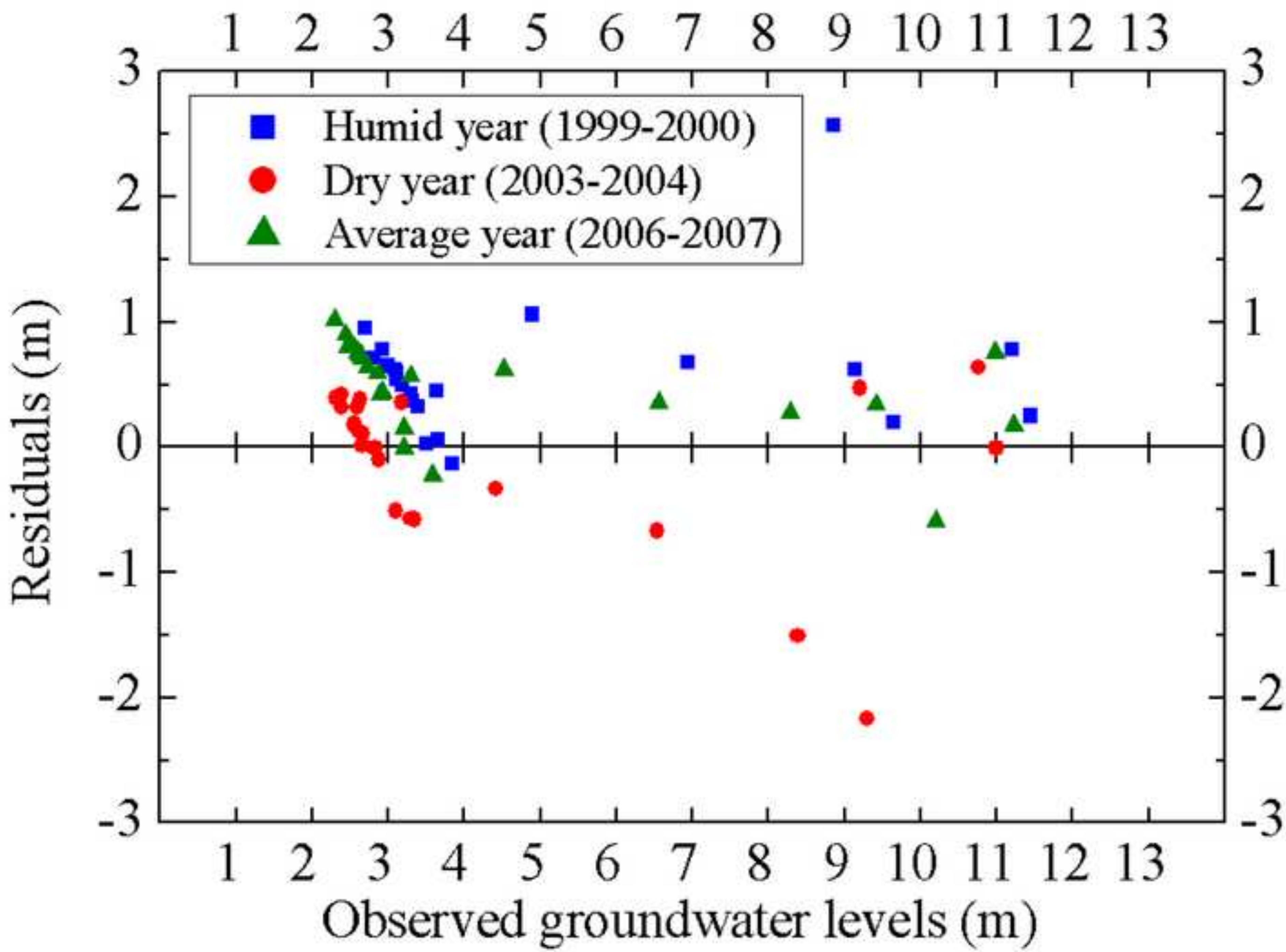

1 2 3 4 5 6 7 8 9 10 11 12 13
3
2
1
0
-1
-2
-3
Humid year (1999-2000)
Dry year (2003-2004)
Average year (2006-2007)
Residuals (m)
Observed groundwater levels (m)

Figure6

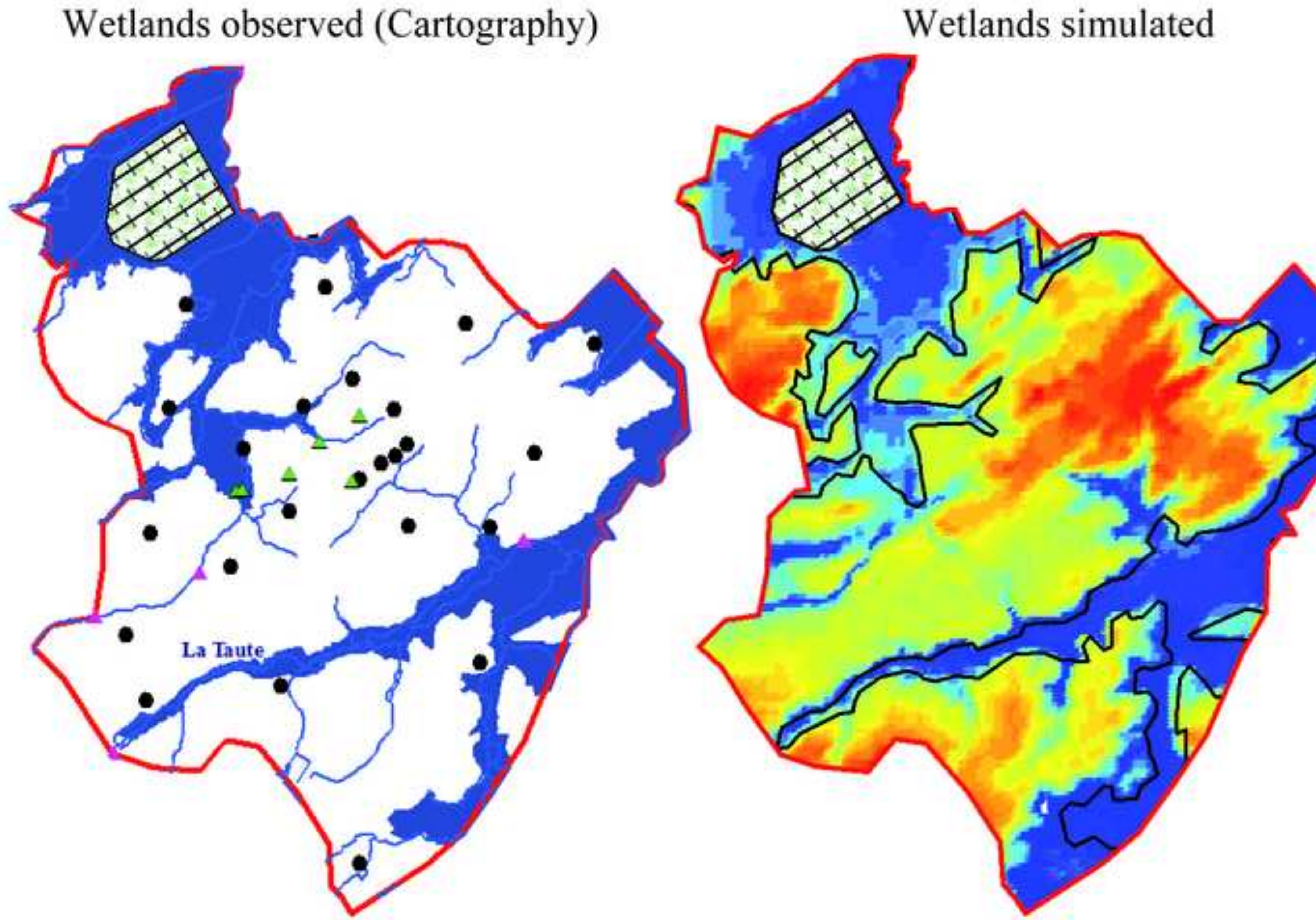

Wetlands observed (Cartography)
Wetlands simulated
La Taute
Water depth [m]
0.00
0.50
1.50
3.00
5.00
7.50
12.0
16.0
22.0

Figure7

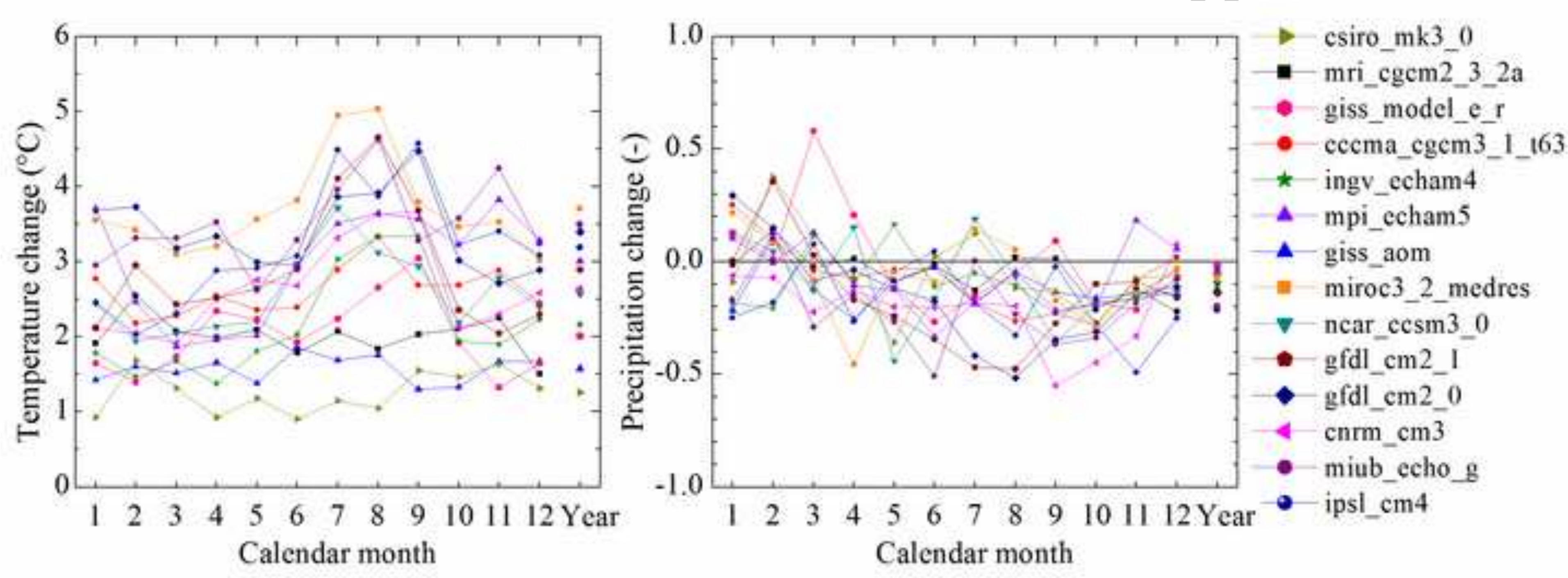
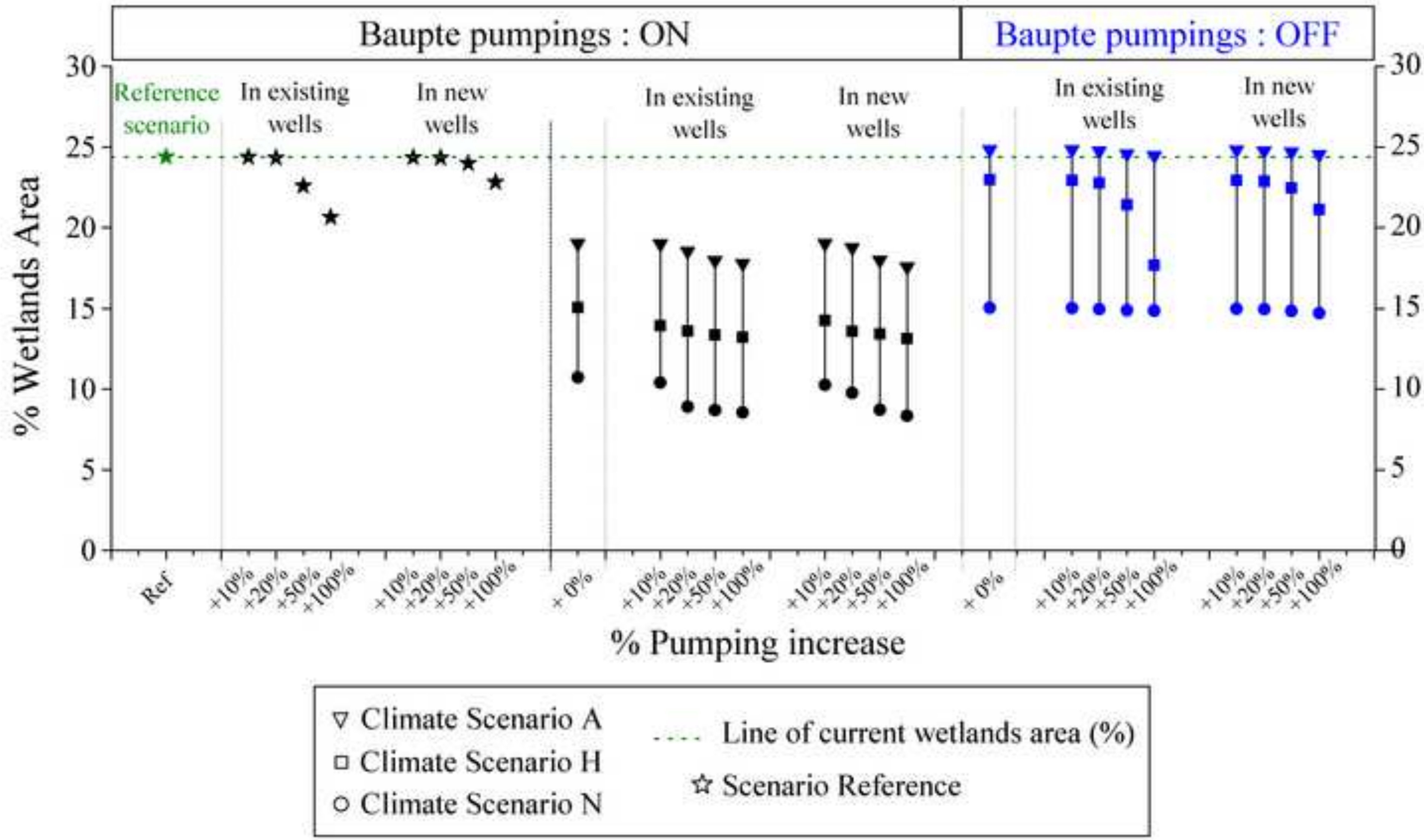

Temperature change (°C)
Calendar month
Precipitation change (-)
Calendar month
1 2 3 4 5 6 7 8 9 10 11 12 Year
csiro_mk3_0
mri_cgcm2_3_2a
giss_model_e_r
cccma_cgcm3_1_t63
ingv_echam4
mpi_echam5
giss_aom
miroc3_2_medres
ncar_ccsm3_0
gfdl_cm2_1
gfdl_cm2_0
cnrm_cm3
miub_echo_g
ipsl_cm4

Figure8



Baupte pumpings : ON
Baupte pumpings : OFF
Reference scenario
In existing wells
In new wells
% Wetlands Area
% Pumping increase
Ref
×10% ×20% ×50% ×100%
× 0%
Climate Scenario A
Climate Scenario H
Climate Scenario N
Line of current wetlands area (%)
Scenario Reference

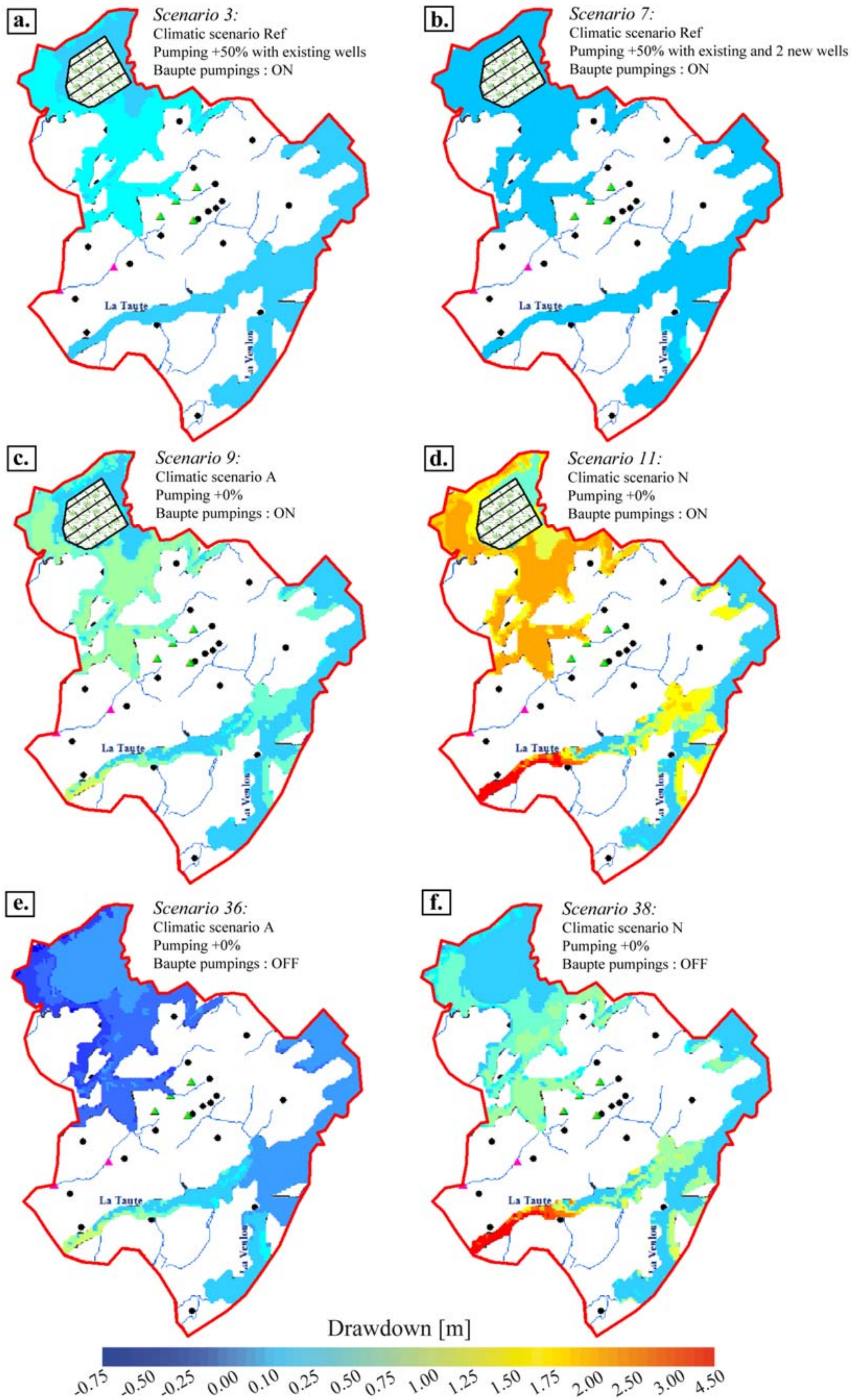

a.
Scenario 3:
Climatic scenario Ref
Pumping +50% with existing wells
Baupte pumpings : ON
b.
Scenario 7:
Climatic scenario Ref
Pumping +50% with existing and 2 new wells
Baupte pumpings : ON
c.
Scenario 9:
Climatic scenario A
Pumping +0%
Baupte pumpings : ON
d.
Scenario 11:
Climatic scenario N
Pumping +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
La Taute
La Venlou
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

Highlights

- Investigating impacts of climate change and groundwater pumping on wetland extension
- Simple model to understand surface-subsurface interaction and wetland vulnerability
- Climate change has a greater impact with loss of wetland area by 5.3 to 13.6%
- The impact of groundwater abstraction would lead to a maximum decrease of 3.7%
- Effects of climate and pumping could be reduced by stop pumping in peat exploitation