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Four Decades of Progress in Monitoring and Modeling of Processes in the Soil-Plant-Atmosphere System: Applications and Challenges

Modelling of drainage and hay production over the Crau aquifer for analysing impact of global change on aquifer recharge

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Abstract

Changes in climate and land use affect water resources and agricultural production. It is important to document these changes and to provide prospective scenarios for improving knowledge and tools that will help stakeholders to anticipate their impacts and propose adaptations. The recharge of the aquifer in the Crau plain mainly depends on the irrigation, in excess, of grassland producing high quality hay. The sustainability of this system is challenged by possible decreases in water availability from the Durance River, the main water source for irrigation, and the decrease in irrigated grassland surfaces. We implemented a modelling system combining the STICS crop model, used in a distributed mode, and the MODFLOW aquifer model for analysing the evolution of hay production, aquifer recharge and water level in the aquifer. The modelling system was implemented for several scenarios concerning climate and land use evolutions, as well as water availability for irrigation, in a close future (2025-2035). The main results showed that the level of the aquifer is seriously threatened by a decrease in irrigation level, either because of a reduction of irrigated grassland surfaces, or because of a limitation of water availability for irrigation. Conversely, the hay production (in term of quantitative yield) would be enhanced by the increase in temperature, even in situation of reduction of irrigation.

Keywords: global change; climate change; aquifer recharge; irrigation; grassland; crop model; aquifer model; distributed modeling;

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1. Introduction

Global change is affecting water resources and agricultural production. All over the Mediterranean Basin, agricultural production is strongly related to the availability of water for irrigation which depends on climate and on other water uses (e.g. domestic, energy production, preservation of wetlands…). Today it is very important to acquire knowledge and to develop tools for predicting impacts of possible changes in climate and water uses and for defining adaptations of agricultural systems. The SIRRIMED project addresses issues related to sustainable uses of water in Mediterranean irrigated agricultural systems, with the overall aim of optimizing irrigation water use. The proposed approach is based on an Integrated Water Resources Management framework dedicated to irrigation where the improved water use efficiency is considered at farm, irrigation district and watershed scales. This framework is being implemented over pilot sites in Spain, France and Greece. In France, the Crau aquifer in the lower Rhone Valley was chosen because of the questions raised by stakeholders involved in the management of water resources and agricultural production toward the possible impact of global changes.

The Crau plain (600 km^2) is the paleo-delta of the Durance River. It is located immediately East of the present delta of the Rhône River, which is also known under the name of Camargue. The recharge of the aquifer (550 km^2) in the Crau plain depends on the irrigation of around 15000 ha of meadow using water withdrawn from the River Durance through a dense network of channels. It is important to notice that there is no natural river network over the Crau plain and that all the water transfers occur in the artificial channel network. The Crau aquifer provides the main resource in domestic water for the 300,000 inhabitants in the area. It is also an important resource for several industrial complexes and for agriculture and has strong downstream connections with protected wetlands. Traditional irrigation practices, since the XVIth century, consist in flooding the grassland fields with a large amount of water, the excess being drained toward the water table. The recharge of the aquifer is mainly originating from these irrigated grasslands. The contribution of irrigation to the recharge is estimated between 50% and 80% of the total recharge depending on the methods used to do the estimation [1][2]. This uncertainty is a major difficulty for the management of water resources in the area. The other main land uses in the area are represented by orchards (~5000 ha), which are irrigated thanks to micro-irrigation techniques using water withdrawn from the aquifer, and a large dry steppic area (~15000 ha), called coussouls, which is hosting several endangered wildlife species and benefits of a strong natural area protection status (National Reserve). Contribution of these other land uses to the recharge of the aquifer only results from their response to rain. Irrigated grassland and dry grassland present strong interactions in terms of agricultural production systems. Traditional pastoral sheep breeding uses the two types of grasslands for grazing. The irrigated grasslands produce high quality hay with a Controlled Designation of Origin label. Thanks to the high density of water channels which supply water to hedgerows, the irrigated grassland area also appears as a bocage landscape and is protected as part of the Natura 2000 Crau site.

Global changes raise questions on the sustainability of the traditional hay production / irrigation system in the Crau plain (this system also includes the sheep breeding and the natural area conservation). Changes in available water from the Durance River may occur in the future because of modifications in the precipitation regime in the French Alps, where the Durance watershed is located, and modifications of the allocation of Durance water to different uses such as hydroelectricity production, recreational uses and protection of river stream ecosystems. Changes also concern land use, in particular replacement of hay production by other crops with different irrigation practices (e.g. orchards with drip irrigation systems) or by urbanized area. Agricultural practices may have to adapt to possible increasing water shortage, implying the development of more efficient irrigation technique. In the last years, we have undertaken the distributed modelling of irrigated meadows together with the modelling of the aquifer in order to provide information and tools for quantifying the contribution of the irrigation to the recharge of the aquifer and to investigate possible evolution of hay production, water drainage, evapotranspiration and water table level under scenarios of climate and land-use changes.

2. Modelling

The approach was to distribute (or spatialize) a crop model that simulated irrigated grassland production processes over the Crau area and to transfer drainage simulated with the distributed crop model to an aquifer model (assuming drainage was equivalent to recharge). Other land uses were included by using simplified models that were based on simplified water budget accounting for the balance of evapotranspiration, rain and drainage. The crop model used to simulate grassland production and drainage was STICS [3][4]. It was implemented on every grassland field. A library of code developed at INRA and called MultiSimLib was used for running multiple simulations of STICS [5] and a specific module for spatially distributing input and output of MultiSimLib was implemented. In order to represent agricultural practices and their spatial variability, statistical approaches were developed [6][2] that distributed practices over the area from available climatic and spatial information (soil properties, field dimensions, water delivery regulations at the irrigation district level, Controlled Designation of Origin regulations, rain…). In the Crau area, spatial distribution of soil properties was also an issue since irrigation had a large impact on soil properties through the deposition of sediment; this information was not available in current soil maps [6][2]. The aquifer model used in the study was built using the Visual-Modflow software (Waterloo Hydrogeologic Inc). To present, this model was only used in a steady-state flow regime. Surface model results were evaluated in [6] and [2] thanks to plot experiments and information from farmers (biomass production, downward water flow, quantity of irrigated water, mowing calendar…) while the aquifer model results were calibrated against piezometer data. Further tests of the coupled model are undergoing.

2.1. Crop model

STICS is a model that has been developed at INRA (France) since 1996 [3][4]. It simulates crop growth as well as soil water and nitrogen balances driven by daily meteorological data. It calculates both agricultural variables (yield, input consumption…) and environmental variables (water drainage, nitrogen losses…). STICS is made up of a number of original parts relative to other crop models (e.g. simulation of crop temperature…) combined to parts based on well-known relationships or on simplifications of existing models. One of the key elements of STICS is its adaptability to various crops. This is achieved by the use of generic concepts relevant for most crops and their specific application for each crop (in terms of eco-physiology, interactions with climate, soil and management practices). As inputs, STICS requires information on soil permanent characteristics, soil initial conditions, daily climate and crop management: see Fig. 1. STICS was adapted for grassland by [7] and tested with success for various types of grasslands by [8]. The model was specifically adapted for analysing the impact of climate change, including CO_2 effect (e.g. see the recent CLIMATOR program in [9]). A specific calibration package, OptimiSTICS, is also available [10][5].

2.1.1. Soil water dynamics

The description of soil includes four compartments: micropores (textural porosity), macropores (structural porosity), fissures (in the case of swelling clay soils) and stones. Water transfers in the micropores compartment are performed for each 1 cm layer using a tipping bucket approach. Water supplies cascade down filling up the layers until field capacity. The permanent features of the 1 cm layers (field capacity, permanent wilting point and bulk density), as well as the initial water contents, are deduced from those prescribed for 5 horizons describing the soil. The macropores and fissures compartments play a role in drainage and run-off processes. The macropores functioning is simulated at the level of the horizon (not per cm) whereas the fissures are supposed to be independent of the layer/horizon soil partitioning. For each horizon, a daily infiltrability parameter is defined that can limit the amount of infiltrated water thereby filling up the macropores in the horizon. When stones are present, the permanent features of the horizons are modified according to the amount and type of stones. The type of stone is characterised by a bulk density and a water holding capacity. In the case of the Crau area, soil parameters were set according to the texture and to the high proportion of stone (often in the order of 80%). At the moment, the impact of stones on the infiltration rate, as well as the impact of consolidated soil layers that are present in most of the Crau area, is not known in details. However, local field experiments by [11] using time-lapse electrical resistivity tomography (ERT) showed that 50 to 60 % of the water added by irrigation were reaching groundwater, about 7-8 m deep, in the next three days after irrigation. Drainage computed by STICS was split in two parts corresponding to drainage of irrigation water and drainage of rain water.

2.1.2. Crop growth processes

Crop growth is driven by the plant carbon accumulation, that is, by the amount of photosynthetically active solar radiation (PAR) intercepted by the foliage and then transformed into aboveground biomass. Part of the latter (harvest index) is accumulated into the harvested organs during the final phase of the crop cycle. The crop nitrogen content depends on the carbon accumulation and on the nitrogen availability in the soil. According to the plant type, crop development is driven either by a thermal index (degree-days), a photothermal index or a photothermal index taking into account vernalisation. The development module is used (i) to predict the time-evolution of leaf area index and (ii) to define the harvested organ filling phase. Water and nitrogen stress reduce leaf growth and biomass accumulation on the basis of stress indices that are calculated from the ratio between soil offer and plant demand. Water demand depends on potential evapotranspiration, nitrogen demand on plant weight (dilution curves). For perennial grasslands as in La Crau, specific processes were introduced that made it possible to the plant to re-grow after grass cuts.

2.2. Spatial distribution and agricultural practices models

STICS simulates crop processes at the plot scale. This corresponds to a specific combination of input variables (climatic data, initial soil variables, crop input data, parameters for soil and crop functioning) and is termed a USM: Unit of SiMulation. Each USM corresponds to one execution of the STICS model. In order to simulate multiple fields over the whole study site, the STICS crop model was used in conjunction with MultiSimLib, a software developed for running the model on a large number of plots with different crop management practices, climate and soils [5]. MultiSimLib allows one to automatically perform STICS simulations for a list of USMs. This software is a library of functions implemented in Matlab (Mathworks, Natick, MA) for manipulating model inputs and outputs, automating multiple simulations, and realizing uncertainty analysis and sensitivity analysis. A new extension to MultiSimLib was developed here for the spatial distribution of the crop model and for mapping outputs. It used a map of agricultural fields all over the Crau area and related each field to a specific USM thanks to a field identifier. This unique identifier was used to create a spatial link between the input and the output of MultiSimLib and the maps stored in the GIS system used for the study: land use and land cover classes, soil classes, meteorological station or meteorological grid. This part of the code also contained procedures to map crop management practices (calendar and amount), in particular irrigation and grass cut (to produce hay), and to account for specific characteristics of the soil in the Crau area, in particular the depth of the surface loam layer that developed thanks to sediment carried by irrigation water. These procedures were described in [2] and [6]. All the input variables and maps needed to run the system are presented in Figure 1.

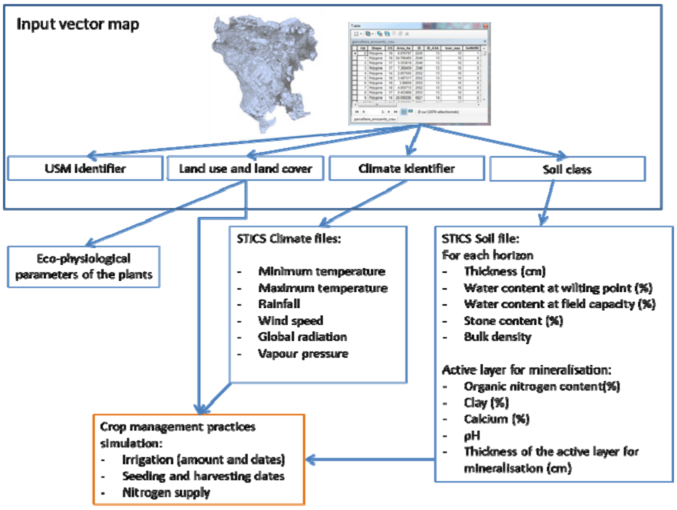

Fig. 1. Structure of the input data used to simulate crops over the Crau area using MultimSimLib and STICS

2.3. Aquifer model

The unconfined aquifer of the Crau is formed by the deltaic depositional system of the Durance River, which was developed from the Pliocene to the Upper Pleistocene. The successive avulsions of the meandering Durance River led to a heterogeneous composition of the Plio-Pleistocene deposits, which varies from conglomerate, more or less consolidated, to clayed lenses [12]. The average and maximum thicknesses of the aquifer are about 15 m and 45 m respectively. The average depth of the water table is about 5 m, while the average thickness of the saturated zone is 10 m. Aquifer recharge has two origins: (1) diffuse recharge due to rainfall all over the area and (2) localised recharge by irrigation water over the irrigated grassland. Groundwater essentially flows from the North-East to the South-West boundary where either it is partially drained by swamps and canals or it reaches the confined Camargue aquifer [13]. Using finite-difference approximations, the partial differential groundwater flow equation was solved with the MODFLOW code [14]. For that purpose, the model of the aquifer was discretized into a regular grid of 149 rows and 191 columns, where each cell is a 200 m by 200 m square. The average drainage fluxes simulated by the surface models for each field of the aquifer area were aggregated to specify the recharge rate to be applied in each cell. The spatial distribution of hydraulic conductivity was calibrated using the water heads observed during the 2003 – 2012 period, on 53 observation wells.

3. Global change scenarios

Analysis of possible evolutions of climate, hydrologic conditions, and land use were performed by [2] and [15] in the frame of the Sirrimed European project (http://www.sirrimed.org/) and of the Astuce et

Tic National project [15]. They were based on long term meteorological records, future climate simulations from the previous IPCC exercise (scenarios A1B, B1 and A2), surveys of the variations in land use in the early past and forecast for the next future, and simulated land use evolutions from the analysis of the socio-economical pressures experienced by the region. Main findings showed that:

- ***i)*** temperature increase was well established since 1980 with a rate of 0.5 °C each 10 years; this trend continues in the next future,
- ***ii)*** annual precipitation has not changed significantly since the beginning of the XIXth century; however the last 50 years show that rainfall decreased in some locations by up to 3 mm year^{-1}; in the next future rain may be decreasing at a rate lower than 1 mm year^{-1},
- ***iii)*** reference evapotranspiration *ETo* (computed using the FAO56-PM method [16]) has increased and will increase significantly (around 1.5 – 2 mm year^{-1}) in the close past and the next future,
- ***iv)*** Durance river flow rate regularly decreases in the future indicating significant changes in the precipitation regime over the collecting watershed; this may affect the level of water available for irrigation in the future,
- ***v)*** irrigated grassland area has decreased by 800 ha between 1997 and 2009 (from remote sensing mapping); depending on hypothesis on the economic development of the region, an additional decrease by 6 to 11 % can be forecasted for 2030; most of the reduction in irrigated grassland area are concentrated around urban centres and correspond to the spreading of urbanized area,
- ***vi)*** Durance water repartition to the different water uses (hydroelectricity, recreational use, agriculture, domestic, stream ecosystems conservation) will be affected by evolutions in the electricity market and the price of water in the next future, as well as by the strengthening of the measures to protect river ecosystems.

These findings served as the basis for defining the future scenarios that were analyzed in this study. These scenarios are summarized in Table 1. We considered two periods, 2003-2010 as a reference (present state or close past) and 2025-2035 as a future period. The future period was chosen not too far in time in order to stay in the frame of acceptable expectations for farmers and other stakeholders. The scenarios (Table 1) considered the climate for the two periods (IPCC scenario A1B), the land use as mapped in 2009 and as forecasted for 2030 assuming an economic development based on the development of service industry around the small urban centers in the North of the area (rather than the industrial development around the port zone at the South of the area), and 30% reduction in available water for irrigation. A drastic change in water availability was imposed in order to account for the combination of the many factors that can affect water availability from the Durance River in the future. This extreme case was chosen in order to provide a low baseline for the analysis of future scenarios.

4. Results

Simulated hydrological balance and grassland yield for the different scenarios are presented in Table 1. Drainage, expressed as recharge rate, computed by the surface models and water table computed by the aquifer model in steady state mode are presented for three scenarios in Figure 2, 3 and 4. Figure 2 shows the distribution of mean recharge rate and the water table (water heads) for the reference scenario *ref_a* which considered “present” conditions in terms of climate, land use and water availability. This scenario corresponded to the observation period 2003 – 2010. Using a typical value of 10% for the porosity of alluvial material, the volume of groundwater was estimated to about 553 hm^3 (Tab. 1). Mean recharge rates (Fig. 2a) were directly linked to land use: above 2 mm day^{-1} for irrigated grasslands, below 0.2 mm day^{-1} for dry grasslands (coussouls) and between 0.4 mm day^{-1} and 1.5 mm day^{-1} for the other crops (arable crops, orchards…). The proportion of irrigation water that was drained toward the aquifer under the grassland areas was evaluated to 75 %. This represented around 80% of the total recharge (Tab. 1). Indeed, drainage of water from rain was less efficient than drainage of irrigation water because of the high amount of water applied for each irrigation event, around 150 mm. This proportion was in the range of existing estimations of the contribution of irrigation to the recharge (50 to 90 %). The water table map (Fig. 2b) shows a strong North East – South West gradient along which water was flowing.

Table 1. Characteristics of the scenarios and simulated impacts on several terms of the annual hydrogeological balance of the area and on the average grassland yield. Scenarios are described in terms of climate period (2006 represent 2003-2010; 2030 represents 2025-2035), land use, water availability for irrigation. nc means not calculated.

Scenario	Climate	Land use	Water availability	Rain	Irrigation volume	Evapo-transpi-ration	Drainage	Drainage of irrigation water under grassland	Part of irrigation water in drainage	Volume of ground-water	Yield (hay)
			(%)	(hm^3)	(hm^3)	(hm^3)	(hm^3)	(hm^3)	(%)	(hm^3)	($t\ ha^{-1}$)
ref_a	2006	2009	100%	294	297	321	277	217	78%	553	8.2
ref_f	2030	2009	100%	311	312	359	275	223	81%	554	9.0
ref_r	2030	2030	100%	311	nc	nc	247	195	79%	521	nc
rte	2030	2009	70%	311	221	352	190	146	76%	440	8.4
rte_sc2	2030	2030	70%	311	220	318	192	140	73%	446	8.4

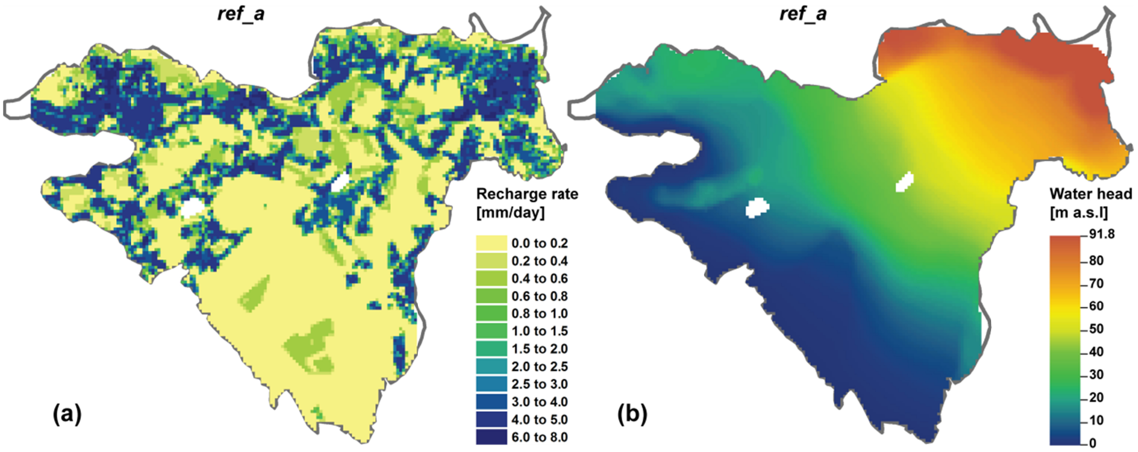

Figure 2 (a) Spatial distribution of the average daily recharge simulated with surface models over the 2003-2010 period (reference scenario *ref_a*); (b) water table expressed as the spatial distribution of water heads (simulated for scenario *ref_a* under steady-state conditions). Aquifer East-West axis is 38.2 km and South-North axis is 29.5 km. North is at the top of the map.

Figures 3 and 4 compare the recharge rates calculated for the foresight scenarios (*ref_f* and *rte_sc2*) with regard to the recharge rate calculated for the present state (scenario *ref_a*). Scenario *ref_f* differed from *ref_a* only for climate. Scenario *rte_sc2* differed from *ref_a* for all the sources of variations (climate, land use and water availability). Scenario *ref_f* showed that recharge rates, and in consequence water heads, were almost not changing because of climate change alone (Fig. 3a and 4a): differences in recharge rate ranged from -0.2 mm day^{-1} to +0.2 mm day^{-1}. This resulted in very low changes in water heads ranging between -0.2 m and +0.2 m which was small compared to the average thickness of the saturated zone. These results were consistent with values of Table 1 that indicated an increase of evapotranspiration over the Crau area balanced by an increase of irrigation water input and an increase in precipitation. This was particularly true for irrigated grassland where drainage slightly increased. Calculation, not presented here, showed that the increase in potential evapotranspiration estimated in the future resulted in an increase of grassland evapotranspiration by 10% in 2025-2035 compared to present, which had a significant impact on the amount of irrigation water required to sustain the level of aquifer recharge and the level of the water table. Conversely, evapotranspiration increase implied a decrease of recharge rate in the Coussouls area (however, it was small since recharge rate was already small in present conditions as shown in Fig. 2a).

In contrast, the spatial distribution of recharge rates calculated for *rte_sc2* was depleted with variable intensity when compared to those of scenario *ref_a* (Fig. 3b). The decrease reached high values above 5 mm day^{-1} in areas where irrigated grassland were converted into urbanized areas (which were not irrigated and more impermeable than agricultural land). Large changes (over 1.5 mm day^{-1}) were also noticed in the irrigated grassland areas where irrigation was decreased by 30% (but change in drainage of irrigation water was larger: 35%). In *rte_sc2* the decrease of recharge rates led to a significant and spatially variable reduction of water heads (Fig. 4b). The average reduction of water heads was 2 m and was reaching more than 7 m in zones of low permeability that were directly concerned by recharge reduction. At the South-West boundary, the water table decrease was buffered by the draining system that forced the water head. Using a porosity of 10%, the volume of the groundwater was estimated to about 446 hm^3 for scenario *rte_sc2* (Tab. 1), which represented a decrease of 19% compared to the present state (scenario *ref_a*). Such a water head decrease led to the drying out of several sectors of the aquifer. Scenario *ref_r* which was considering changes in climate and land use (Tab. 1) showed that the reduction in irrigated grassland area by 11% resulted in a decrease of drainage of irrigation water by 13%. Water heads decreased by up to 4 m around the new urbanized areas (map not shown). The decrease of the quantity of water stored in the aquifer, by more than 30 hm^3, was equivalent or larger than the withdrawal for agricultural use or for domestic use.

Concerning production of hay, the comparison between future (*ref_f*) and present (*ref_a*) scenarios indicates that the increase in temperature in the future may result in an increase in yield (+ 10% in 2030 compared to now). Yield was also increasing in scenario with reduction in irrigation level (*rte* and *rte_sc2*).

5. Summary

We developed a modelling framework for simulating the relation between irrigated production and aquifer recharge under various global change scenarios. It was applied to the Crau area in the lower Rhone Valley in France showing that:

- irrigated grasslands play a major role in the Crau aquifer recharge and, more generally, in the water cycle over the area
- future increases in temperature and in reference evapotranspiration, together with an adequate management of irrigation, may lead to an increase in hay production
- decrease in drainage, either because of a limitation of available water for irrigation, or because of the replacement of irrigated grasslands by other land uses, in particular urban areas, may lead to a significant decrease of the aquifer storage, threatening the sustainability of groundwater and its dependent ecosystems in the area.

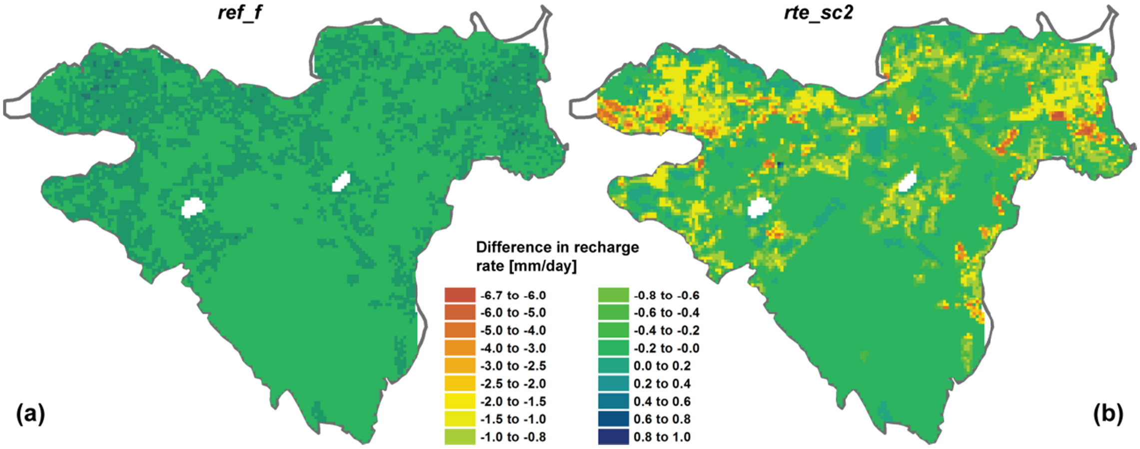

Figure 3. Differences between the calculated recharge of scenarios *ref_f* (change in climate) and *ref_sc2* (change in climate, land use and water availability) and the calculated recharge for the reference scenario *ref_a* (close past to present conditions). Figure (a): *ref_f*.; Figure (b): *rte_sc2*.

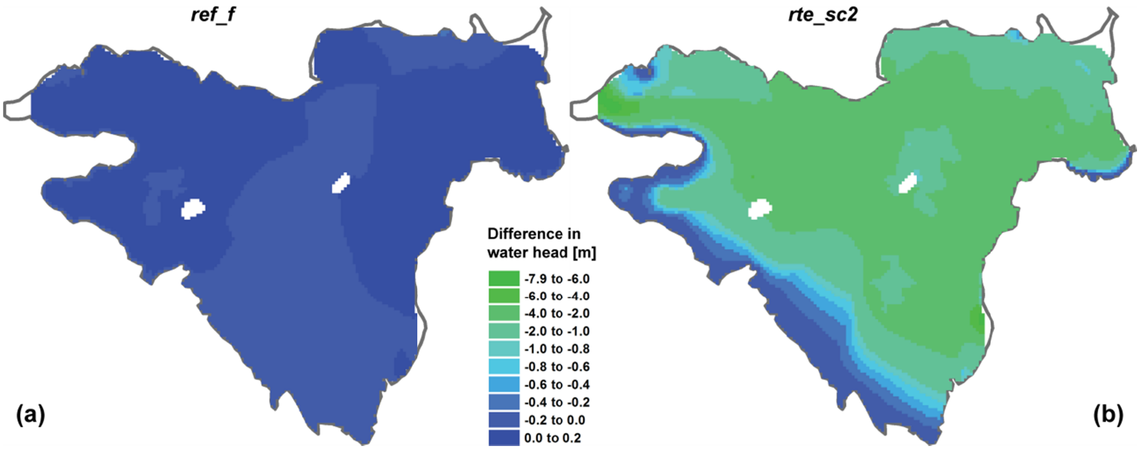

Figure 4. Differences between the calculated water heads of scenarios *ref_f* (change in climate) and *ref_sc2* (change in climate, land use and water availability) and the calculated water heads for the reference scenario *ref_a* (close past to present conditions). Figure (a): *ref_f*; Figure (b): *rte_sc2*.

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