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Simulation of future groundwater recharge using a climate model ensemble and SAR-image based soil parameter distributions — A case study in an intensively-used Mediterranean catchment

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HIGHLIGHTS

- Future groundwater recharge has been projected for the Thau catchment (France).
- Simulations indicate no clear trend of decreasing groundwater recharge.
- Soil parameters from soil maps and SAR-images lead to comparable simulation results.

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ABSTRACT

We used observed climate data, an ensemble of four GCM–RCM combinations (global and regional climate models) and the water balance model mGROWA to estimate present and future groundwater recharge for the intensively-used Thau lagoon catchment in southern France. In addition to a highly resolved soil map, soil moisture distributions obtained from SAR-images (Synthetic Aperture Radar) were used to derive the spatial distribution of soil parameters covering the full simulation domain. Doing so helped us to assess the impact of different soil parameter sources on the modelled groundwater recharge levels. Groundwater recharge was simulated in monthly time steps using the ensemble approach and analysed in its spatial and temporal variability. The soil parameters originating from both sources led to very similar groundwater recharge rates, proving that soil parameters derived from SAR images may replace traditionally used soil maps in regions where soil maps are sparse or missing. Additionally, we showed that the variance in different GCM–RCMs influences the projected magnitude of future groundwater recharge change significantly more than the variance in the soil parameter distributions derived from the two different sources. For the period between 1950 and 2100, climate change impacts based on the climate model ensemble indicated that overall groundwater recharge will possibly show a low to moderate decrease in the Thau catchment. However, as no clear trend resulted from the ensemble simulations, reliable recommendations for adapting the regional groundwater management to changed available groundwater volumes could not be derived.

1. Introduction

The Mediterranean region is among the Hot-Spots which are the most responsive to global climate change (Giorgi, 2006). According to current climate projections, Mediterranean river basins are at high risk to changes in the hydrological cycle. These changes are expected to have noticeable impact on the sustainably available groundwater resources (Taylor et al., 2012). Especially in regions where public, industrial and agricultural water supply is largely covered by groundwater, detailed knowledge about the volumes of natural groundwater recharge is of great importance. Groundwater recharge is generally a transient process mainly controlled by the interaction of climate variables as

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well as land surface, soil, and geological characteristics. Hence, climate change may have different effects on groundwater recharge in a catchment area depending on the interplay of site specific site-conditions. As groundwater recharge and its vulnerability to climate induced changes are not observable directly, it is commonly investigated using numerical simulation approaches (Leavesley, 1994). As a precondition for their application, area-covering data-sets of climate variables and the parameters which characterise land surface, soil, and geology of a study area must be available. In Mediterranean catchments, this data basis is often incomplete or of low quality. Thus, simulation results of groundwater recharge models are associated with considerable uncertainties and decisions in groundwater management risk to cause unsustainable exploitation of groundwater resources.

One important variable in groundwater recharge modelling is soil moisture. Soil moisture plays a crucial role in the continental water cycle, in particular through its influence on the distribution of precipitation between surface runoff and infiltration, which is the main driver behind most hydrological and geomorphologic processes. Additionally, evapotranspiration depends essentially on soil moisture. Thus, soil moisture is simulated area-wide by state-of-the-art groundwater recharge models but in practice rarely validated by observed data. In recent years, remote sensing data have been increasingly investigated to serve as observed references (Vereecken et al., 2008).

Synthetic Aperture Radar (SAR) is often used for the estimation of soil moisture. In addition, SAR-images can be made under all meteorological conditions (clouds, fog, etc.) and at any time of the day. Over the last three decades, several studies using SAR-data revealed a high sensitivity of the radar signal to soil moisture for bare soils or zones with little vegetation cover, especially in the first few centimetres of soil. The penetration depth of the radar waves is related to soil moisture: higher soil moisture contents clearly lead to lower penetration of the radar signal. Bruckler et al. (1988) found that in a clay loam soil, the penetration depth of C-band (wavelength ~6 cm) radar signals decreased from approximately 5 cm in the case of 10 vol.% soil moisture, to 1 cm when the soil moisture increased to 30 vol.%. Moreover, several studies showed that the radar signal increases linearly with soil moisture, for moistures ranging between approximately 5 vol.% and 35 vol.% (e.g. Aubert et al., 2011, 2013; Baghdadi et al., 2006, 2008; Holah et al., 2005; Le Toan et al., 1994; Ulaby et al., 1986). At higher soil moisture contents, the radar signal stabilizes and then decreases (e.g. Baghdadi et al., 2008; Holah et al., 2005). Results also showed that an accuracy between 3 and 6 vol.% on the soil moisture estimates can be achieved from SAR-data over bare soils and dispersed vegetation areas (Aubert et al., 2013; Baghdadi et al., 2007, 2011, 2012). The presence of dense vegetation cover prevents accurate soil moisture estimates due to the strong vegetation attenuation that reduces the sensitivity of the radar signal to soil moisture. Quesney et al. (2000) showed for wheat that the C-band radar signal at VV polarization (incidence angle of 23°) was highly sensitive to soil moisture (about 0.30 dB/vol.%) at an early vegetation stage (high plant water content and vegetation layer height below 30 cm), with an accuracy on the soil moisture estimates of about 5 vol.%. At the end of the growth stage, the sensitivity of the radar signal to soil moisture becomes negligible (0.02 dB/vol.%) and the estimation of soil moisture becomes unreliable because the radar signal attenuation through the vegetation is at its maximum (height about 90 cm and high plant water content). In the senescent period, the sensitivity reaches 0.2 dB/vol.% (low water content induces low vegetation contribution to radar signal) and the estimation of soil moisture is accurate once again (about 5 vol.%). In X-band (radar wavelength about 3 cm), Hajj et al. (2014) showed at an incidence angle of 30° that the sensitivity of the radar signal to soil moisture decreases as the leaf area index (LAI) of irrigated grassland increases. For LAI lower than 2 m^2/m^2, the sensitivity of X-band radar signal to soil moisture at both HH and HV polarisations was approximately 0.13 dB/vol.%. However, for LAI higher than 2 m^2/m^2, this sensitivity decreases to 0.088 and 0.064 dB/vol.% at HH and HV, respectively.

Remotely sensed soil moisture patterns can also serve as data basis to retrieve soil parameters for modelling purposes. A recent overview concerning this matter is given by Montzka et al. (2011). Groundwater recharge models, such as the mGROWA model (Herrmann et al., 2013), necessarily require soil parameter distributions, namely soil moisture at field capacity (Θ_{fc}) and soil moisture at the permanent wilting point (Θ_{pwp}). Such parameters are commonly derived from soil maps available in the respective study area. Soil moisture distributions derived from SAR-images correspond to these parameters under certain circumstances. SAR-images taken after long rainy periods at the end of the hydrological winter half-year may represent the distribution of soil moisture at field capacity. SAR-images taken after long drought periods, e.g. during the hydrological summer half-year, may represent the distribution of soil moisture at the permanent wilting point. Consequently, a suitable time series of SAR-images can be used to derive the distribution of soil parameters necessary for the mGROWA model. Against this background, a procedure to transfer SAR-image based soil moisture information (Baghdadi et al., 2012) into area-covering soil parameter distributions applicable in mGROWA was developed.

In order to reduce existing uncertainties and quantify climate induced impacts on different components of the hydrologic cycle in Mediterranean catchments, the CLIMB project (Climate Induced Changes on the Hydrology of Mediterranean Basins — Reducing Uncertainty and Quantifying Risk) was established and funded by the EC's 7th Framework Programme (Ludwig et al., 2010). In CLIMB, a model chain has been established consisting of global climate models (GCMs), regional climate models (RCMs) and water balance models, including the mGROWA model. The model chain was applied to the catchment of the Thau lagoon in southern France, where already nowadays water needs of the different consumers are not covered by natural water resources (La Jeunesse et al., 2015).

In this article we intend to answer three main questions: (1) Are there differences in mGROWA simulation results for groundwater recharge in the Thau catchment in case SAR-image based soil parameter distributions are used instead of soil maps? (2) Can SAR-image based soil parameter distributions be recommended to be used in water balance models instead of soil maps? (3) Will there be an impact of climate change on future groundwater recharge in the Thau catchment?

2. Catchment characteristics

The Thau lagoon is located in the Languedoc-Roussillon Region in the south of France (Fig. 1). The catchment covers approx. 280 km^2. The rivers Vène and Pallas are the two main natural tributaries to the lagoon. Their catchments cover an area of 67 km^2 and 54 km^2, respectively, and contribute more than 50% of total freshwater inflow into the lagoon (Plus et al., 2006; Sellami et al., 2013). In addition, the catchment area is drained by a dozen of intermittent small streams that flow directly into the lagoon. Half of the catchment can be considered as ungauged, which required the development of methods to assess the discharge of all the sub-catchments of the Thau catchment (Sellami et al., 2014). However, there is no continuous discharge record available as discharge was monitored only temporarily in the framework of research projects.

The Thau lagoon itself is a 75 km^2 water body, 19.5 km long and 4.5 km wide, with a mean depth of 4 m and a high variability of salinity. Approximately one fifth of the lagoon (1500 ha) is intensively farmed by shellfish production (oysters and mussels). Frequent anoxic crises are a consequence of high eutrophication levels (La Jeunesse and Elliott, 2004) and particular meteorological conditions (Chapelle et al., 2000). The amount of freshwater coming from the catchment is a driver of the ecological status of the lagoon and also for the transfer of microbial contaminants impacting shellfish production. Thus, the freshwater volume needs to be assessed to run the ecological model of the Thau lagoon (Chapelle et al., 2000) as well as Decision Support Tools (Mongruel et al., 2013).