Science of the Total Environment 543 (2016) 937–951

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Sensitivity of mGROWA-simulated groundwater recharge to changes in soil and land use parameters in a Mediterranean environment and conclusions in view of ensemble-based climate impact simulations

L. Ehlers [a,b,*], F. Herrmann [a], M. Blaschek [b], R. Duttmann [b], F. Wendland [a]

[a] *Forschungszentrum Jülich GmbH, Institut für Bio- und Geowissenschaften, Agrosphäre (IBG-3), D-52425 Jülich, Germany*
[b] *Christian-Albrechts-Universität zu Kiel, Geographisches Institut, D-24118 Kiel, Germany*

HIGHLIGHTS

- Future groundwater recharge was simulated using the water balance model mGROWA.
- Four different GCM–RCM combinations were used as climate forcing.
- Sensitivity of model output to changes in selected parameters was examined.
- Simulation results indicate significantly reduced groundwater recharge by 2100.

ARTICLE INFO

Article history:
Received 8 January 2015
Received in revised form 25 March 2015
Accepted 30 April 2015
Available online 15 May 2015

Keywords:
Water balance simulations
Groundwater recharge
Semi-arid environment
mGROWA
Climate change
Climate projections
GCM–RCMs
CLIMB project

ABSTRACT

This study examines the impact of changing climatic conditions on groundwater recharge in the Riu Mannu catchment in southern Sardinia. Based on an ensemble of four downscaled and bias corrected combinations of Global and Regional Climate Models (GCM–RCMs), the deterministic distributed water balance model mGROWA was used to simulate long-term mean annual groundwater recharge in the catchment for four 30-year periods between 1981 and 2100. The four employed GCM–RCM combinations project an adverse climatic development for the study area: by the period 2071–2100, annual rainfall will decrease considerably, while grass reference evapotranspiration will rise. Accordingly, ensemble results for our base scenario showed a climate-induced decrease in the median of annual groundwater recharge in areas covered by *Macchia* from 42–48 mm/a to 25–35 mm/a between the periods 1981–2010 and 2071–2100, corresponding to a reduction of 17–43%. To take into account the influence of additional plant available water storage in weathered bedrock on groundwater recharge generation, the model was extended by a regolith zone for regions covered by Mediterranean *Macchia*. In a set of model runs ("scenarios"), parameter values controlling the water storage capacity of this zone were increased step-wise and evaluated by comparison to the base scenario to analyze the sensitivity of the model outcome to these changes. The implementation of a regolith zone had a considerable impact on groundwater recharge and resulted in a decrease of the median in annual groundwater recharge: by 2071–2100, the 35% scenario (available water content in the regolith of 3.9 to 5.7 vol.%) showed a reduction of 67–82% as compared to the period 1981–2010 in the base scenario. In addition, we also examined the influence of changes in the crop coefficients (K_c) as well as different soil texture distributions on simulated groundwater recharge.

1. Introduction

The Mediterranean region is "among the most responsive regions to global change" (Giorgi, 2006) and expected to be severely affected by advancing water scarcity as a consequence of a projected further decrease in mean annual rainfall as well as an increasing variability of summer precipitation (IPCC, 2007). Over the past decades, an increase in sea surface temperature-linked sea evaporation as well as a drop in precipitation has been registered, which in turn exhibits considerable inter-decadal variations (Mariotti, 2010; Mariotti and Dell'aquila, 2012). Already, droughts represent a serious economic threat to the Mediterranean countries. For instance, the 2003 summer drought caused a reduction of 36% in the net primary production of maize in

* Corresponding author at: Øster Voldgade 10, DK-1350 Copenhagen, Denmark.
E-mail addresses: lbe@geus.dk (L. Ehlers), f.herrmann@fz-juelich.de (F. Herrmann), blaschek@geographie.uni-kiel.de (M. Blaschek), duttmann@geographie.uni-kiel.de (R. Duttmann), f.wendland@fz-juelich.de (F. Wendland).

http://dx.doi.org/10.1016/j.scitotenv.2015.04.122
0048-9697/

the Po valley, Italy (Ciais et al., 2005). Extremely dry conditions affected the entire western Mediterranean between 2006 and 2008 (Lopez-Bustins et al., 2013).

The EU-funded research project CLIMB ("Climate-induced Changes on the Hydrology of Mediterranean Basins", 7th Framework Program) aimed at quantifying the impact of changing climatic conditions on catchment hydrology in a set of study areas located throughout the Mediterranean (Ludwig et al. 2010). The Riu Mannu di San Sperate catchment in southern Sardinia is one of the investigated areas. The catchment is characterized by intensive agricultural activity and has experienced a successive decrease in precipitation and a period of extremely dry summers in recent years.

In the frame of the CLIMB project, Mascaro et al. (2013) performed hydrological simulations for the Riu Mannu catchment using the physically based distributed model tRIBS. The authors presented an approach to compensate for scarcity of hydro-meteorological data and to generate the required forcing for their simulations. They used a subset of a historic discharge record (1930–1932) to calibrate and temporally downscale precipitation and potential evapotranspiration to an hourly resolution, obtaining good results with regard to model performance. Furthermore, Piras et al. (2014) used the tRIBS model and assessed the impact of changing climatic conditions on water resources in the Riu Mannu catchment by comparing results for a reference (1971–2000) and future period (2041–2070). Their findings indicate reductions in most water balance components, including mean annual runoff, soil water content and groundwater table.

In contrast to the studies cited above, our work focused particularly on the impact of changing climatic conditions on groundwater recharge in the Riu Mannu catchment. We performed water balance simulations for four 30-year periods between 1981 and 2100, using the water balance model mGROWA (Herrmann et al., 2013) and four combinations of Global and Regional Climate Models (GCM–RCMs). To take into account additional plant available water storage in weathered bedrock, the model was extended by a regolith zone for regions covered by Mediterranean *Macchia*. Several studies indicated that this type of vegetation is able to withdraw water from the regolith zone through tap roots. Unfortunately, the information content of the soil maps available for the Riu Mannu catchment did not suffice to permit a robust, spatially distributed characterization of the parameters controlling the soil water storage capacity for locations covered by *Macchia*. Since it was assumed that the parameters of the regolith zone have a considerable influence on the water budget, the available water content θ_a of the regolith zone was increased step-wise in a sequence of model runs ("scenarios"). The results were then evaluated by comparison to a base scenario to analyze the sensitivity of the model outcome to these changes. Moreover, simulations were performed for two sources of pedological information: a soil texture distribution based on a soil map by Aru et al. (1990) and one derived through interpolation of sampled data using compositional kriging (cf. Section 3.2.1). Finally, further simulations were performed for different sets of crop coefficients K_c.

It should be noted that the simulation results presented in this study are affected by different sources of uncertainty. There are three major sources of uncertainty (Walker et al., 2003): Firstly, there is input uncertainty which concerns the model forcing data and arises from measurement errors or data inaccuracies. Inaccuracies are for instance a result of generalized, inter- or extrapolated (e.g. precipitation) and spatially aggregated information (land use and soil maps). Secondly, as models necessarily use simplified process descriptions to reproduce physical processes, there is always structural uncertainty of a model. Thirdly, parameter uncertainty concerns the parameter values employed in the model.

However, we point out that we did not explicitly quantify the various sources of uncertainties present in this work as this would have exceeded its scope. Instead, we examined the sensitivity of the model outcome to changes in the aforementioned model parameters. A comprehensive quantitative uncertainty assessment (cf. e.g. Refsgaard et al. (2007)) remains to be conducted in a future study.

2. Study area

The Riu Mannu di San Sperate catchment is located in the south of Sardinia and has a drainage area of 472.5 km^2 (Fig. 1, top). The Sardinian Agency for Research in Agriculture (AGRIS) operates an experimental farm in Ussana in the south of the catchment, collecting hydro-meteorological data and monitoring crop productivity. The topography of the catchment is characterized by a relatively plain area in the western and central part and rugged mountainous terrain in the eastern half of the catchment (Fig. 1, i). Elevation ranges between 69 and 961 m a.s.l., with a mean elevation of 297 m a.s.l. and a mean slope of 8.5°.

The catchment has a Mediterranean-type climate (Peel et al., 2007) which is characterized by an extremely dry summer period and a wet season from September to May. The mean annual precipitation is about 500 mm (De Girolamo et al., 2010), with >90% of the annual precipitation falling in winter (Mascaro et al., 2013). The Riu Mannu di San Sperate is a 35 km long river course and has its headwaters in the north of the catchment. The flow regime is dominated by low flows throughout the year (<1 m^3/s) and the irregular occurrence of high flows (and potentially overbanking) after extreme rainfall events. The river drains into the Flumini Mannu near Monastir in the south-west of the catchment. As there is currently no discharge gauge, the catchment can be classified as "ungauged" in the sense of Sivapalan (2003). The lack of a discharge record made model validation and calibration to discharge observations impossible (cf. Section 3.3).

The economy in the Riu Mannu catchment largely depends on intensive and often irrigated agriculture (Fig. 1, ii). With regard to the agricultural production, durum wheat represents the most frequently cultivated crop (37%). Other land uses include olives, clover, vineyards as well as orchards, alfalfa and corn silage (De Girolamo and Lo Porto, 2012). Over the past decades, the intensification of agricultural activities in combination with ever increasing amounts of fertilizers led to a decline of water quality in the catchment due to nutrient pollution (De Girolamo et al., 2010).

The prevailing geological units in the study area are post-Variscan Quaternary and Tertiary sediments, which cover most of the western half of the catchment. Towards the eastern margin of the catchment, metamorphic rocks belonging to the *Sarrabus* and *Gerrei* formation as well as a complex of volcanic intrusions can be found (Fig. 1, iii, based on Carmignani et al. (2011)). Natural vegetation is dominated by Mediterranean-type *Macchia* scrubland, which is a sclerophyllous shrub formation. Typical species include holm oak (*Quercus ilex*), cork oak (*Quercus suber*), tree phillyrea (*Phillyrea angustifolia L.*), wild asparagus (*Asparagus acutifolius*), lentisk (*Pistacia lentiscus L.*), juniper (*Juniperus phoenicea L.*) and wild olive (*Olea silvestris*) (Detto et al., 2006). *Macchia* vegetation is well adapted to dry conditions and has high water use efficiency (Marras et al., 2011).

3. Data and methods

3.1. Brief model description

The following paragraphs are intended to outline the basic functionalities and equations of the mGROWA model. A comprehensive description of the mGROWA model is given by Herrmann et al. (2013).

The water balance model mGROWA was designed for applications in medium-sized to large catchments and administrative units such as Federal States (Herrmann et al., 2013). The model design enables the simulation of groundwater recharge at a high resolution, which represents the main target variable of the mGROWA model. The model resolution is arbitrary and can be tailored to the purpose and scale of investigation. For the present study, a cell size of 50 m was deemed