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Global change and agricultural management options for groundwater sustainability

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ABSTRACT

According to the general circulation models (CGMs) for future climate projections, a temperature increase, precipitation decrease, and an increase in the variability of extreme events may be expected in the future, likely reducing available water resources. For the western Mediterranean, future climate change projections indicate that temperature increase may range from 1.5 °C to 3.6 °C, and the precipitation decline will reach between 10% and 20%, which may result in a significant reduction of natural groundwater recharge. With the use of modelling tools, the amount of groundwater recharge under different climate change scenarios and varying agricultural management practices can be predicted, and water budget attributes can be estimated, which may allow for quantifying impacts, and assist in defining adaptation strategies. For the Inca–Sa Pobla basin (Balearic Islands, Spain), under future climate change projections, agricultural management alternatives of crop type distribution and irrigation demands are required for planned adaptation strategies. In the area, where irrigation water for agricultural practices originates from groundwater resources, adaptation measures based on a change from mixed crops to potatoes and a 20% decrease of agricultural land cultivation have proven to be efficient for the hydrologic system and associated wetland sustainability.

1. Introduction

During the last century, agricultural production based on vegetable species of rapid growth, intensively irrigated crops and an extensive use of inorganic fertilisers has seen fast development. The most intensive land use, in terms of water and nutrient consumption, corresponds to irrigated agriculture, frequently developed on top of highly vulnerable aquifers (detrital, coarse grained, with a vadose zone less than 30 m thick and low replenishment capacity). Vulnerable aquifers are frequently located in zones of high water demand, such as coastal areas, and groundwater from wells is generally used for agricultural irrigation and water supply (Foster and Candela, 2008). Water cycle interactions are governed by complex processes between climate, soil and vegetation, and despite the great importance of groundwater for agriculture, there is a lack of understanding of the probable impacts of climate change on the resource.

Recent studies based on coupled atmosphere–ocean General Circulation Models (GCMs) for future climate change projections in the Mediterranean region, forecast an increase of temperature and decrease of precipitation (A1B scenario, www.ipcc.ch/publications_and_data/ar4/wg2/en/ch12s12-3.html). Climate change projections also indicate an increased likelihood of drought (Kerr, 2005) and variability of extreme events, which may reduce available water resources. Additionally, water scarcity in soil as a consequence of a decrease of precipitation represents one of the most important stress factors for vegetation.

The most straightforward way of obtaining spatial resolution scenarios is to apply coarse-scale climate change projections (GCMs). In order to obtain more suitable climate change information at regional or sub-regional scale, downscaling techniques classified into two categories (statistical downscaling methods and regional models) are currently applied. Statistical downscaling involves developing quantitative relationships between large-scale atmospheric variables and local surface variables. Stochastic weather generators are widely used for downscaling hydrologic values at local level based on GCM statistical properties. The main statistical techniques and their strengths and weaknesses are presented in Hewiston and Crane (1996).

Assessing the impact of climate change including groundwater recharge and adaptation options to mitigate changes on the hydrologic cycle has been extensively investigated over the last decade by a number of authors. Among them Zekster and Loaiciga (1993), Kracauer Hartig et al. (1997), Kundzewick and Somlyódy (1997), Bouraoui et al. (1999), Allen et al. (2004), Cuculeanu et al. (2004), Wilby et al. (2006), Green et al. (2007), Risbey et al. (2007), Scibeck et al. (2007), Candela et al. (2009), Pumo et al. (2010), and Acreman et al. (2009) can be cited.

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There are few works that combine agricultural adaptive strategies and climate change impact on water resources (Morton, 2007). Published studies indicate that most of the benefits resulting from adaptive strategies take place with a moderate climate change, whilst their effectiveness is limited under more severe climate change (Howden et al., 2007). Besides, a full capacity to implement adaptations is often assumed, but it is not always the case (Morton, 2007). Mortimore and Adams (2001) mention the major elements of adaptation for northern Nigeria, including labour, use of biodiversity in cultivated crops, or the diversification of livelihoods. Swearingen and Bencheifa (2000) and Tubiello et al. (2002) mentioned the strategic use of fallowing, planting times and crop rotation when crops fail to survive drought. Most studies on irrigated systems do not include the implications of a possible reduction in irrigation water availability (Arnell, 2004), as it is expected in Mediterranean area, although the work carried out by Doll (2002) shows that two-thirds of the global area equipped for irrigation will suffer from increased water requirements (net irrigation requirements).

In this study we examine the role of hydrological processes for agricultural management in areas with a high net irrigation demand. The methodological approach is based on coupling downscaled output from the HadCM3 General Circulation Model and a groundwater model to estimate changes in groundwater recharge and impacts of management practices in the quantitative status of an aquifer-fed coastal wetland. Adaptation decisions are based on changes to groundwater exploitation patterns for crop irrigation or water supply, with the purpose of reducing the sensitivity of the hydrologic system to climate change, and increasing its resilience to cope with such change.

1.1. Overview of the region

Majorca is the main island of the Balearic archipelago, located to the northwest of the Mediterranean Sea (Fig. 1). It has a surface area of 3640 km^2, and a maximum altitude of 1443 m. The permanent total population of the island is 869,000 inhabitants (2010), which increases during summer due to tourism.

Majorca's geology is a consequence of the development of the Alpine ranges and its location in the centre of the western Mediterranean basin. The Balearic Islands constitute emerged enclaves of the "Balearic Headland", which is the emerged prolongation of the Betic belt. Majorca is divided into three units according to geology and landscape: the Tramuntana mountain range (northwest), the Llevant mountain range (southeast) and the Central Plains (Fig. 1).

The climate is considered temperate Mediterranean with mild humid winters and hot, dry summers. The annual mean temperature is 17 °C, varying slightly in the mountain range (where snow may be present during winter), and in the warmer coastal regions. The island's average annual precipitation is 625 mm, with precipitation between 1400 mm/y in the Tramuntana mountain range and 400 mm/y in the southern part of the island. A total of 60% of the annual precipitation falls between October and January. According to PHIB (1999), potential evapotranspiration estimated by the Penman-Monteith method accounts for 1025 mm/y for the 1980–2005 period.

Perennial streams do not exist and surface water is reduced to the presence of torrents, which, while accounting for important flow rates during short periods of time, are only significant for long-lasting rainfalls. Around 20% of the total annual precipitation constitutes aquifer recharge. Total renewable water resources of Majorca Island accounts for 494 Mm^3/y, where 374 Mm^3/y correspond to groundwater and 120 Mm^3/y to surface water (PHIB, 1999). Although the contribution of surface water to the potential water resources is about 24%, the real contribution is approximately 1.5%, which means that almost all the water used in Majorca comes from groundwater sources.

The principal water use is for agricultural irrigation, accounting for 61% of the total water demand, although only 10% of the cultivated land is under irrigation. Over 2205 km^2 of agricultural land, 195 km^2 are irrigated with 150 Mm^3/y of groundwater and treated wastewater. The main cultivated crops are cereals, fruit trees (apple, apricot, pear, peach), citrus trees (orange, mandarin, lemon), vegetables, potatoes (two harvests), forage crops (wheat, barley), pulses (bean, string bean) and industrial crops, with a growing season extending throughout the year. During the 1970s and 1980s, the main concern of the agricultural sector was to obtain the maximum productivity of crops. This was achieved as a result of excessive applications of nitrogen fertiliser (more than 450 kg N/ha/y), including ammonia, nitric, ammonia-nitric, ureic, and organic manure fertilisers, which are currently applied in agricultural management.

The northern area of the Central Plains (Fig. 1) of the island, corresponding to the Inca–Sa Pobla, has been selected as a case study. It extends over 360 km^2 with a population that seasonally duplicates, and shows important agricultural activity developed on top of the Quaternary, highly vulnerable upper aquifer. The existing aquifers, especially the upper aquifer, have allowed farmers to benefit from groundwater irrigation. The aquifer, highly exploited for drinking water supply and irrigation, discharges via several springs into a wetland (S'Albufera Natural Park). The uneven spatial and temporal rainfall distribution in combination with the varying total population, water demand for agriculture, as well as tourism, leads to important changes in regional and seasonal water availability. In the study area the main socio-economic aspect is the seasonal variation of population; more than one quarter of the total population are seasonal residents (Donta et al., 2005).

The likely increase in variability of temperature and rainfall, as projected by climate change scenarios, also implies an increasing water demand for agriculture, in competition with other uses. Moreover, groundwater abstraction poses a risk to the wetland's water level.

2. The Inca–Sa Pobla basin

The Inca–Sa Pobla hydrogeologic unit located in the northeast of Majorca Island is the study area chosen for the methodological application (Fig. 1). The selection was made according to the existing hydrologic and socio-economic characteristics, which render the catchment as an ideal case study as it has increasing water demand during the seasonal period, irrigated agriculture development, water management conflict among users and ecological impacts on the S'Albufera wetland. S'Albufera is identified as being of international importance in the RAMSAR convention list.

Seven meteorological stations are located in the area with data sets since 1940. For the 1986–2005 historical period, the mean annual temperature and precipitation were 17 °C and 584 mm, respectively; 60% of the precipitation took place in spring and autumn. Monthly Penmann evapotranspiration accounted for 1200 mm/y.

The area has a low-lying topography, and is surrounded by a hilly landscape of tectonically deformed Mesozoic materials. The unit is a northeast–southwest oriented tectonic subsiding sedimentary basin, filled with post-tectonic Miocene, Pliocene and Quaternary materials of detrital and carbonate origin. Impervious bedrock corresponds to tectonically deformed lower Miocene and Tertiary materials. The basin consists of three separate sub-basins (PHIB, 1999), these being the S'Albufera (near the sea), Sa Pobla (north-east) and Inca (south-west) sub-basins.