Journal of Hydrology 521 (2015) 84–99

Contents lists available at ScienceDirect

Journal of Hydrology

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

Impact of climate and land cover changes on snow cover in a small Pyrenean catchment

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ARTICLE INFO

Article history:
Received 1 February 2014
Received in revised form 12 November 2014
Accepted 22 November 2014
Available online 5 December 2014
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Daqing Yang, Associate Editor

Keywords:
Snow cover
Climate change
Land cover change
Pyrenees

SUMMARY

The seasonal snow in the Pyrenees Mountains is an essential source of runoff for hydropower production and crop irrigation in Spain and France. The Pyrenees are expected to undergo strong environmental perturbations over the 21st century because of climate change (rising temperatures) and the abandonment of agro-pastoral areas (reforestation). Both changes are happening at similar timescales and are expected to have an impact on snow cover. The effect of climate change on snow in the Pyrenees is well understood, but the effect of land cover changes is much less documented. Here, we analyze the response of snow cover to a combination of climate and land cover change scenarios in a small Pyrenean catchment (Bassiès, 14.5 km^2, elevation range 940–2651 m a.s.l.) using a distributed snowpack evolution model. Climate scenarios were constructed from the output of regional climate model projections, whereas land cover scenarios were generated based on past observed changes and an inductive pattern-based model. The model was validated over a snow season using in situ snow depth measurements and high-resolution snow cover maps derived from SPOT (Satellite Pour l'Observation de la Terre – Earth Observation Satellite) satellite images. Model projections indicate that both climate and land cover changes reduce the mean snow depth. However, the impact on the snow cover duration is moderated in reforested areas by the shading effect of trees on the snow surface radiation balance. Most of the significant changes are expected to occur in the transition zone between 1500 m a.s.l. and 2000 m a.s.l. where (i) the projected increase in air temperatures decreases the snow fraction of the precipitation and (ii) the land cover changes are concentrated. However, the consequences on the runoff are limited because most of the meltwater originates from high-elevation areas of the catchment, which are less affected by climate change and reforestation.

1. Introduction

The Pyrenees mountain range is located in southwest Europe between France and Spain (mean latitude 42.4°N) and represents a water tower for the regions of northern Spain and southwest France in which the runoff from the Pyrenean watersheds is used for hydropower production, crop irrigation, urban consumption and power plant supplies. Most of the wintertime precipitation in the Pyrenees falls as snow; therefore, snowmelt is a major contributor to the river discharge in spring and summer when water needs for crop irrigation are the highest (López-Moreno and García-Ruiz, 2004).

The Intergovernmental Panel on Climate Change (IPCC) emphasized that climate change will likely have a more acute effect on the mountainous areas located in southern Europe such as the Pyrenees because of increases of the mean temperatures (Pachauri, 2008; IPCC report, 2013). In addition, a relatively fast and widespread increase in forest cover in the Pyrenees is occurring as a result of the abandonment of rural activities (Vicente-Serrano et al., 2004; Poyatos et al., 2003; Galop et al., 2011).

Both climate and land cover changes are expected to modify the water availability in the lowland areas where the pressure on water resources is already strong (García-Ruiz and Lana-Renault, 2011; López-Moreno et al., 2011; López-Moreno et al., 2014).

Climate model projections have indicated that future climatic conditions are likely to have a substantial impact on the water resource availability in the main Pyrenean basins. Several studies reported an increase in mean annual air temperature of approximately +3 °C by the end of the 21st century in the Pyrenees region, which translates to a decrease in streamflow during the irrigation

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http://dx.doi.org/10.1016/j.jhydrol.2014.11.060
0022-1694/

period because of earlier seasonal snowmelting (Beniston, 2003a; Beniston et al., 2003b; López-Moreno et al., 2008; Majone et al., 2012). The changes in precipitation are more contrasted depending on the season, but a slight decrease in the mean annual value is expected (Majone et al., 2012).

In addition, the ongoing land cover changes have and will continue to have a profound impact on the dominant hydrological processes in the Pyrenees (Gallart and Llorens, 2004; Morán-Tejeda et al., 2010; López-Moreno et al., 2011). Even if some studies conducted in this region (see e.g., López-Moreno et al., 2011; Graveline et al., 2014) showed that in the Ebro catchment, water yield is mainly affected by water consumption and diversions for agricultural activities, Gallart and Llorens (2004) and López-Moreno et al. (2011) attributed a decrease in water yield of the Ebro River to an increase in forest cover in the catchment area. Indeed, many headwater Pyrenean catchments are not yet affected by artificial uptakes. However, possible land cover change impacts on the water resources in the Pyrenees are multiple and thus difficult to isolate at a regional scale (Morán-Tejeda et al., 2010; López-Moreno et al., 2014). In a temperate mountainous region such as the Pyrenees, the possible impacts of land cover changes include changes in evapotranspiration, runoff generation processes and snow melt (e.g., Andréassian, 2004). In the Pyrenees, it has been shown that increasing forest areas led to an increase in evapotranspiration (Gallart and Llorens, 2004; López-Moreno et al., 2011) and to reduce storm runoff intensity during moderate events (Gallart and Llorens, 2004; López-Moreno et al., 2008). Using a hydrological model, Delgado et al. (2010) simulated a decrease in runoff under a reforestation scenario in a small rainfall-Pyrenean headwater catchment. However, to our knowledge, the effect of changes in land cover on the snow cover has not been addressed in the Pyrenees.

Land cover is known to control the snow processes in mountainous areas (see Varhola et al., 2010 for a thorough review of the empirical evidence in the literature). Many studies have investigated the effect of vegetation type on snow accumulation and melting processes (Hedstrom and Pomeroy, 1998; Koivusalo and Kokkonen, 2002; Pomeroy et al., 2002; Lundberg et al., 2004; Mellander et al., 2005; López-Moreno and Latron, 2008). The SnowMIP-2 project (Essery et al., 2009) evaluated the ability of snowpack models to represent forest snow processes. A model comparison was performed to understand the interactions between forest and snow in meteorological, hydrological and ecological modeling. Indeed, when an area is covered by low vegetation, such as grassland or subalpine meadows, snow falls directly on the ground. Conversely, in an area covered by high or intermediate vegetation, such as deciduous or conifer forests, the tree branches intercept a significant amount of snow before it reaches the ground (Andréassian, 2004). The intercepted snow is immediately submitted to sublimation processes and returns to the atmosphere; therefore, forests tend to increase snow interception and decrease snow deposition and accumulation on the ground. This physical process has been shown in numerous studies, and the conclusion is that snow accumulation is lower under the forest canopy than in clearcuts, whereas snow melt rates are slower under forests (Jost et al., 2007; López-Moreno and Latron, 2008; Varhola et al., 2010). If the snow deposition on the ground is reduced, the amount of snow available to the soil is smaller and the snow albedo tends to drop rapidly; the snow albedo is also affected by the "litter effect," which reduces the under-canopy snow albedo because of the deposition of organic materials from the trees (Hardy et al., 2000). By decreasing the snow albedo, high vegetation tends to accelerate the snowmelt. Conversely, a high vegetation canopy tends to shield the snowpack from incoming solar radiation, resulting in lower melting rates than snowpack associated with low vegetation or bare soil (Marks et al., 1998; Talbot et al., 2006). All of these vegetation effects are contradictory during the melting phase, and in a specific area, it is important to understand the processes that produce the greatest snowmelt and if the snow melts faster or slower with higher land cover. The processes by which vegetation influences the snowpack are generally dependent upon the climatic conditions (López-Moreno and Latron, 2008; Essery et al., 2009). Therefore, both climate and land use changes should be considered in a combined framework to estimate the response of the snow cover to future conditions in the Pyrenees.

In the framework of the Pyrenees Climate Change Observatory (OPCC, http://www.opcc-ctp.org), the objective of this study is to gain insights into the likely effects of climate and land-use changes on snow cover in the Pyrenees. The impact of climate change alone on snow and hydrology in the Pyrenees was already investigated in previous studies (Beniston, 2003a; Beniston et al., 2003b; López-Moreno et al., 2008; Majone et al., 2012) and is currently being addressed in the SCAMPEI project (French acronym for climate scenarios designed for mountain areas: extreme phenomena snow cover and uncertainties, Déqué, 2010) by using ad hoc dynamical and/or statistical downscaling of General Circulation Model (GCM) outputs. Here, we aim at characterizing the sensitivity of the snow cover to a likely combination of climate and land cover changes at the end of 21st century at the scale of a small headwater catchment in the Pyrenees. The study area is the Bassiès catchment (14.5 km^2), which is located in the Ariège French department (northeastern Pyrenees). This site was chosen because it is a well-studied and representative area of a common scenario in the Pyrenean massif: after thousands of years of intense agro-silvo-pastoral activities (Galop and Jalut, 1994), the region experienced a rapid rural depopulation during the first half of the 20th century that generated a rapid reforestation at all altitudes (Houet et al., 2012). Since 2009, a Human-Environment Observatory (http://w3.ohmpyr.univ-tlse2.fr/presentation_ohm_pyr.php) was set up in this region by the Institute of Ecology and Environment of the French National Center for Scientific Research (InEE-CNRS) to study the interactions between ecological, hydrological and human society phenomena. For this study, an automatic weather station was installed in the Bassiès area to monitor surface-level meteorological conditions and snow depth. The meteorological forcing observed at the Bassiès station on an hourly basis and the current vegetation map are used to run and validate a snowpack model over the 2011–2012 snow season. We selected SnowModel (Liston and Elder, 2006a), a physically based distributed snowpack evolution model, because it provides a comprehensive framework for snow cover modeling in complex terrain, and can model the spatial interpolation of meteorological input data and simulate physiographic effects on the snowpack, including the typical parameterizations for vegetation effects on snow processes. In addition, it allows a description of the snow cover in two dimensions, which enables a comparison with remote sensing data.

After a description of the study site, data, methods and SnowModel, we investigate the model's ability to simulate snow depth using in situ observations (plot-scale validation) and remotely sensed data (catchment-scale validation). Model projections of snow depth are then produced and analyzed using different temperatures, precipitation amounts and land cover scenarios, first independently and secondly, all combined, to assess the impact of climate and land use changes on the snowpack over the study site. Lastly, expected temperature and vegetation changes are investigated to understand how they impact the different components of the snowpack mass balance and in particular, the meltwater runoff at the basin catchment downstream.