Journal of Hydrology xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Journal of Hydrology

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

Assessing the capability of the SWAT model to simulate snow, snow melt and streamflow dynamics over an alpine watershed

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ARTICLE INFO

Article history:
Received 11 February 2015
Received in revised form 6 October 2015
Accepted 28 October 2015
Available online xxxx
This manuscript was handled by Laurent Charlet, Editor-in-Chief, with the assistance of Melissa Lafreniere, Associate Editor

Keywords:
SWAT
MODIS
Hydrological modelling
Snow simulation
Elevation band
Garonne River

SUMMARY

Snow is an important hydrological reservoir within the water cycle, particularly when the watershed includes a mountainous area. Modellers often overlook water stocked in snow pack and its influence on water distribution, especially when only some portions of the watershed is snow dominated. Snow is usually considered to improve hydrological modelling statistics, but without any regard for the realism of its representation or its influence on the hydrological cycle. This is all the more true when semi-distributed models are used, often considered inadequate for spatially representing such phenomena. On the other hand, semi-distributed models are being increasingly used to realise water budget assessment at a regional scale and such studies should not be realised without a good representation of the snow pack. Lack of field measurements is also a frequent justification for avoiding validating simulated snow packs. In this study, remote sensing data provided by MODIS is combined with *in situ* data, enabling the validation of the snow pack simulated by the Soil and Water Assessment Tool (SWAT), a semi-distributed, physically-based model, implemented over a partly snow-dominated watershed. Snow simulation was performed without complex algorithms or calibration procedures, using the elevation bands option included in the model and related snow parameters. Representation of snow cover and hydrological simulation were achieved by a standard automatic calibration of the model, over the 2000–2010 period, performed by SWAT-Cup/SUFI2, using six hydrological gauging stations along the fluvial continuum downstream of the snow-dominated area. Results highlight three important points: (i) Set-up of elevation bands over mountainous headwater improved hydrological simulation performance, even well downstream of the snow-dominated area. (ii) SWAT produced a good spatial and temporal representation of the snow cover, using MODIS data, despite a slight overestimation at the end of the snow season on the highest elevation bands. A comparison of the model estimate of snowpack water content with *in situ* data revealed an underestimation in water content in the lower part of the watershed and a slight overestimation in its upper part. Those errors are linked and originate from difficulties of the model to incorporate very local spatial and temporal variations of the precipitation lapse rate. (iii) Elevation bands brought consistent changes in water distribution within the hydrological cycle of implemented watersheds, which are more in line with expected flow paths.

1. Introduction

Water production is undeniably linked to mountainous areas that often contribute between 40% and 60% of global discharge, an estimation that can increase regionally up to 95% (Viviroli and Weingartner, 1999; Viviroli et al., 2003). Therefore, in hydrological modelling, snowfall, snow accumulation, and snowmelt are among processes that have the greatest impact on the global water cycle. Differences in their estimation may cause substantial changes to hydrological simulations (Verbunt et al., 2003; Zeinivand and Smedt, 2009). This is all the more true when watersheds are located wholly or partly in mountains where, by temporarily storing water, snow affects the timing and amplitude of the seasonal

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http://dx.doi.org/10.1016/j.jhydrol.2015.10.070
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hydrograph. Furthermore, many studies have highlighted the importance of taking snow processes into account when evaluating climate change impact (Barnett et al., 2005; Douville et al., 2002; Gurtz et al., 2005; Viviroli et al., 2011). Some models incorporate snow processes exclusively (Coughlan and Running, 1997; DeBeer and Pomeroy, 2009; Garen and Marks, 1996; Martelloni et al., 2012), using anything from a degree-day formulation to more complex energy budgeting to simulate snowmelt. From an operational point of view, there are two main ways of accounting for snow in hydrological models. The most common method is to use the snow pack reservoir in the model only to improve performance on discharge simulation, without verifying the adequacy of the snow pack simulation in terms of water content, spatial distribution and temporal evolution (Troin and Caya, 2014; Wang and Melesse, 2005). The second method simulates snowpack conditions (Pradhanang et al., 2011) in order to obtain a good representation of the "snow water storage" as a part of the hydrological cycle. The latter approach is often constrained by the availability of *in situ* snow data with appropriate spatial and temporal resolutions. In this context, remote sensing is a valuable source of critical data. For instance, MODIS (Moderate Resolution Imaging Spectroradiometer) is one of the most used remotely-sensed snow data sources (Hall and Riggs, 2007; Klein and Barnett, 2003).

Regardless of whether validating snowpack or not in a model, studies concerned with the hydrological impact of snowmelt are often confined to watersheds immediately downstream of the principal snow accumulation areas – often small in size. Few studies have gone further by including downstream basins in their analysis. However, it is essential to take the influence of snow on the hydrological cycle into account, to improve water management on a larger scale, even if the watershed is not strictly snow dominated.

The Soil Water Assessment Tool (SWAT) model (Arnold et al., 1993) is a physically-based, comprehensive, continuous, semi-distributed and watershed-scale simulation model that allows the simulation of a large number of physical processes. It has been successfully implemented in many locations (Douglas-Mankin et al., 2010; Gassman et al., 2007). It includes a snow module, allowing the delimitation of up to ten elevation bands with associated temperature and precipitation lapse rates (Fontaine et al., 2002; Luo et al., 2012; Rahman et al., 2013).

In a previous study, Zhang et al. (2008) tested the benefits on SWAT discharge and runoff simulations to model snow without elevation bands, with elevation bands, and even with another more complex algorithm: SNOW17. Their results showed that using elevation bands is much more efficient than without. However, the use of a more complex algorithm failed to enhance discharge simulation and their conclusions were entirely based on hydrological performance and did not deal with the realism of snow representation.

The present study attempts to take the analysis further. It looks at determining how far SWAT is able to represent snow in terms of spatial and temporal distributions and stored water quantity. The analysis relies on a standard calibration procedure, i.e. based only on stream flow observations. No direct calibration of the snow pack or the snow water equivalent is realised, but these are assessed using MODIS and *in situ* data. Previous studies (Hong et al., 2010; Ouyang et al., 2010; Park et al., 2013; Stehr et al., 2009; Strauch and Volk, 2013) have experimented using MODIS data, but simply to validate SWAT streamflow simulations. Only Stehr et al. (2009) have assessed the use of MODIS as a source of snow distribution data for validate SWAT snow simulations for a small, entirely snow-dominated basin, where no other data were available. The present study examines a much larger area than the Stehr et al. (2009) study (455 km^2), focusing on the upper part of the Garonne River watershed (9200 km^2), which drains a mountainous region. Another limitation of our study is the lack of reservoir management data to set up the SWAT model, a relatively common problem in hydrology, given the difficulties associated with obtaining such data from operators. The work presented here has thus been conducted without reservoir management data. The last part of the paper is dedicated to analysing how changes in snow dynamics representation influence SWAT water budget.

Several studies have been carried out in the investigated region. Fischer (1932), Pardé (1936) and Probst (1983) provide comprehensive hydrological descriptions of the Garonne watershed. Voirin-Morel (2003) applied the hydrometeorological model ISBA-MODCOU, while Sauquet et al. (2010) used MODCOU and GR4J to simulate discharge over the Garonne River Watershed. Following from their work, Caballero et al. (2007) and Dupeyrat et al. (2008) tested the response of the Garonne River to climate change using CEQUEAU and ISBA-MODCOU.

Preliminary studies have also been performed using SWAT. Chea (2012) and Pinglot (2012) assessed pros and cons of using SWAT over this diversified catchment. They highlighted the important role played by snow accumulation and snow melt over the catchment. However, most SWAT applications on the Garonne focused on low altitude segments, deprived of the influence of snow (Boithias, 2012; Boithias et al., 2011; Ferrant et al., 2011; Oeurng et al., 2011).

Hence, the objectives of this study are: (i) to explore the various snow representation possibilities, including elevation bands, offered by SWAT; (ii) to validate SWAT snow simulations using MODIS data supplemented with *in situ* data; (iii) to assess the impact of different snow dynamics computation on SWAT water budgets.

2. Materials and methods

2.1. Study area

The Garonne River is 525 km long and one of the principal fluvial systems in France, draining a 55,000 km^2 area located in southwest France into the Atlantic Ocean. The large range of altitudes and slopes within the watershed leads to a diversity of hydrological behaviours that could be attributed to three geographic entities: the Pyrenees to the south, the Massif Central to the north-east, and the plain between them (Probst, 1983).

The Pyrenean portion of the watershed largely influences the hydrological regime and consists of high mountains (some peaks exceed 3000 m) above a large plain, whose elevation is less than a few hundred meters (Fig. 1). This portion, which represents nearly one sixth of the Garonne watershed and is largely influenced by topographic factors (Probst, 1983), is the focus of the present study. The Pyrenees portion of the Garonne River Watershed, which covers 9200 km^2, has its outlet at Portet where an average flow of 189 m^3/s (1910–2013) has been reported. The highest discharge on record reached 4300 m^3/s and the lowest was 23 m^3/s. Over the same period, when looking at inter-annual mean monthly values, the highest flows occurs in May (348 m^3/s) and the lowest in September (84 m^3/s). Elevation ranges from 150 m to 3145 m, while 44% of the watershed has an elevation below 500 m and 20% above 1500 m (Fig. 1). Land use analyses from Corine Land Cover maps (CLC, 2006) reveal that the plain is dominated by crops and pastures. Agricultural activities represent 49% of the watershed, while the hillsides of the Pyrenees (35% of the watershed) are covered by forests. For altitudes above 2500 m, vegetation is composed of alpine grassland and shrub.

According to the FAO soil classification on the European Soils Data Base map (ESDB, 2006), the soil composition is dominated by different types of cambisols (65% of the catchment). Similar to

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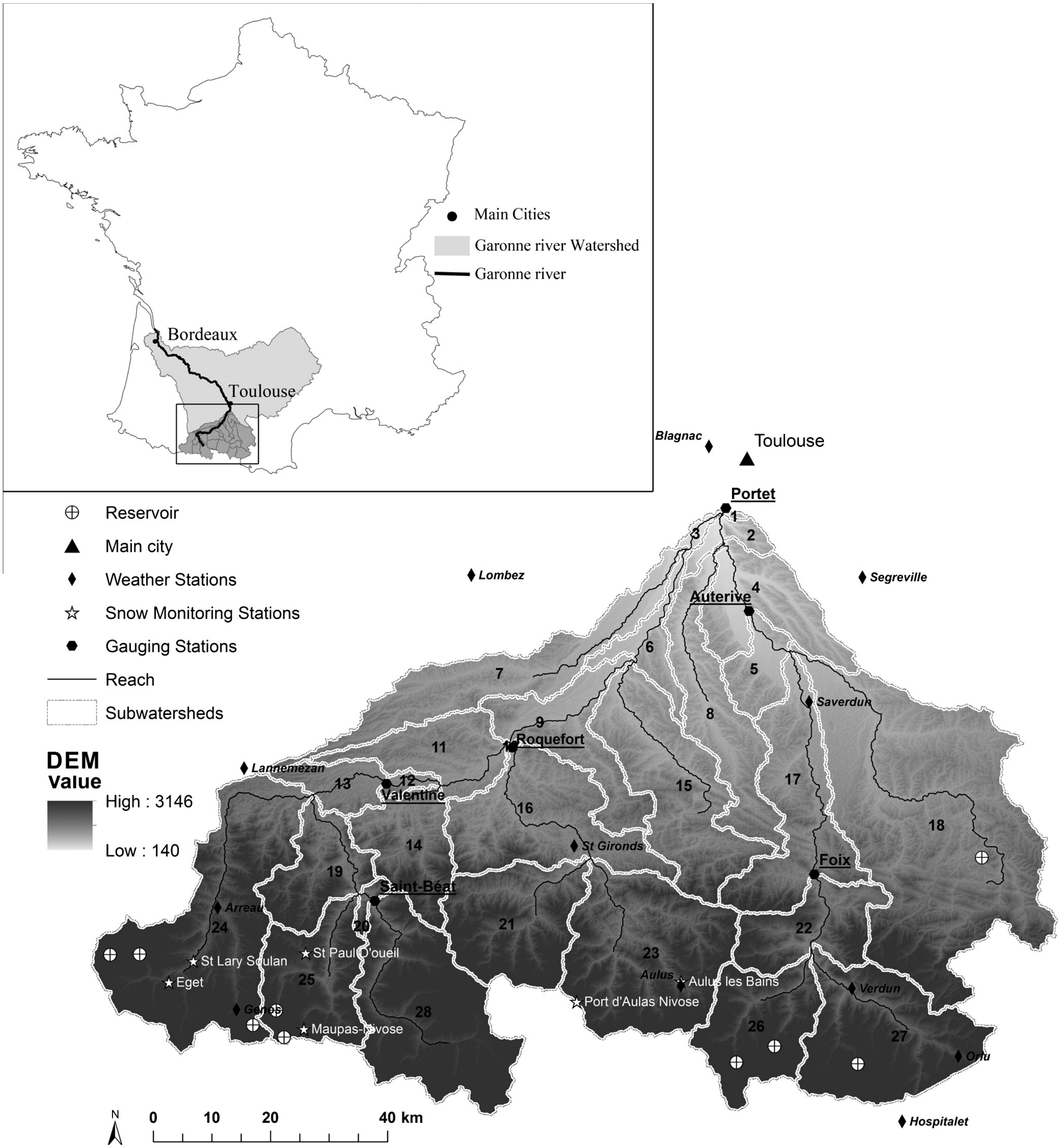

Fig. 1. Geographic situation of the headwater Garonne watershed.

the land use conditions, existing soil types differ with terrain condition and altitude. In the plain, calcic cambisol (27%) is dominating on eutric podzoluvisol (6%) orthic luvisol (6%) and fluvio-calcic fluvisoil (9%) that are present along streams. Slopes of the Pyrenees are dominated by dystic cambisols (32%) associated with orthic rendzina (5%). Above 2500 m, soil composition is divided between humic cambisols (5%), ranker (6%), and lithosols (3%).

Climate across the entire Garonne watershed does not reflect the same level of variability as for the Pyrenees. In the mountains, temperatures fall below freezing during winter months, while the winter temperatures in the plain generally remain positive. Dessens and Bücher (1997) stressed the variability of the Pyrenean precipitation, especially in winter when totals may be up to three times higher in the mountains than in the plain. In terms of temperature, analysis of Météo-France weather data provides a good example of this variability. Throughout the 2000–2010 period, mean minimum and maximum temperatures at the Genos station (1250 m) in February were – 3 °C and 3.5 °C respectively. For the same period, the Blagnac station (151 m), only 120 km away, shows mean minimum and maximum temperatures of 3 °C and 11.5 °C (Fig. 1). Variability in air temperatures associated with altitude the terrain causes irregularity in snow distribution: for

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instance the mountainous areas are snow dominated during winter while snow is absent in the plain all year long.

The watershed is also impacted by human activities, mainly by the presence of several dams obstructing the natural flow of the river. Subbasins 18, 24, 25, 26 and 27 (Fig. 1) account for most of the reservoirs, which are primarily used for low flow support. Consequently, those reservoirs impact the hydrologic regime during the summer and the autumn but have a limited effect on the simulation of the snow processes. In Sauquet et al. (2010) and Hendrickx and Sauquet (2013), observed discharge data and naturalized discharge data are compared at four gauging stations: Valentine, Roquefort, Foix and Portet (Fig. 1). This comparison highlights the limited impact of human activities on discharge during winter. Of the four gauging stations, only Foix seems to be partly impacted, over the January–March period. It should also be noted that this influence is not transmitted downstream to the Portet station.

2.2. SWAT model

SWAT was developed to simulate the impact of land use changes on hydrology, water quality and erosion. It is a semi-distributed model, based on a discretisation of the area. The first step of this discretisation consists in dividing the watershed into sub-watersheds, based on topography. SWAT then identifies hydrological response units (HRUs) within each sub-watershed, based on soil, land use, and slope. The HRUs are then used to compute a water balance based on four reservoirs: snow, soil, shallow aquifer, and deep aquifer. The main hydrological processes include infiltration, runoff, evapotranspiration, lateral flow, and percolation. Water balance computation is performed at the HRU level, aggregated at the subbasins level, and routed towards the reaches and the catchment outlet. The SWAT model has been chosen for this study because it has been successfully applied worldwide, over a wide range of scales, topographies, and climate conditions. It also allows the modeller to simulate various hydrological fluxes and reservoirs including snow (Douglas-Mankin et al., 2010; Gassman et al., 2007, 2014). ArcSWAT 2012, which includes a GIS-based graphical interface, has been used for this study to define subwatersheds, HRUs and generate input files for the model.

For its water budget, SWAT distinguishes solid and liquid precipitation based on near-surface air temperature. The snowfall temperature parameter (SFTMP) is compared to the mean daily air temperature at subbasin scale; if it is lower than SFTMP, precipitation is then considered solid. If precipitation is considered solid, it is accumulated until snowmelt.

Snowmelt is mainly controlled by the air and snowpack temperature along with the daylight hours. Water volume generated by snowmelt process over a subwatershed, also depends on the extent of the snow cover. Table 1 shows modifiable parameters related to snow at the catchment level. A more comprehensive description of equations used by SWAT can be found in Neitsch et al. (2011).

In SWAT, snowfall, snowpack, and snowmelt processes are always computed by the model as soon as the temperature falls below the threshold of snowfall temperature. But it also enables those processes to be spatially refined as a function of elevation. A maximum of ten elevation bands can thus be defined for subbasins as appropriate. Precipitation and temperature are then taken into account for each individual elevation band, exploiting two lapse rates: one for temperature (*tlaps* in °C/km) and one for precipitation (*plaps* in mm H_2O/km/yr).

In this paper, the benefits of different snow computing and calibration options are tested. Three different projects are set up: a first one, as a reference, without regard to snow calibration, a second one using basin-scale global snow parameters, and a last one using elevation band discretization and lapse rates. Table 2 and Fig. 1 identify the seven subbasins where this last variation has been implemented (see Section 2.4 for more details).

Table 1
Modifiable snow parameters.

SWAT parameters	Description	Default values
SFTMP	Snowfall temperature	1.0 °C
SMTMP	Snowmelt temperature	0.5 °C
SNO_SUB	Initial snow water content	0 mmH_2O
SNOCOVMX	Snow water content for 100% snow cover	1.0 mmH_2O
SNOW50COV	Fraction of SNOCOVMX corresponding to 50% snow cover	0.5
SMFMX	Snow melt factor on 21 June	4.5 mmH_2O/°C-day
SMFMN	Snow melt factor on 21 December	4.5 mmH_2O/°C-day
TIMP	Snowpack temperature lag factor	1.0

SWAT elevation bands (Fontaine et al., 2002) are set up by specifying their number, their mean elevation, and the proportion of the subbasin area they encompass. However, there is no consensus in the literature on a recommended number of elevation bands. Among the few studies dealing with this issue, some define bands as a function of elevation (Fontaine et al., 2002; Luo et al., 2012; Rahman et al., 2013; Stratton et al., 2009), while others define them as a function of area (Pradhanang et al., 2011; Stehr et al., 2009; Zhang et al., 2008). The number of bands varies from 1 to 10. Fontaine et al. (2002), who developed the snow module, found that using 5 altitudinal bands improved simulation. As far as the authors are aware, only Pradhanang et al. (2011) have compared simulations with various numbers of bands (0, 1, 3, and 5). They concluded that using three or five elevation bands improved simulation. However, the topography of their watershed was not as pronounced as for the Garonne: 800 m instead of 2530 m (Table 2). Ten elevation bands were therefore set up here.

2.3. Model setup

2.3.1. GIS layer and meteorological data sets

Table 3 identifies the data sources used to set up the model. In order to delineate the watershed and compute the flow directions of the river system, a digital elevation model (DEM) with a 90 m resolution from NASA and METI was employed (ASTER, 2011). Land uses come from the Corine Land Cover (CLC, 2006) map on a scale of 1:100,000. The catchment is divided up into 25 land use types. Soil data are derived from the European Soil Database (ESDB, 2006) map on a scale of 1:1,000,000, which relies on FAO soil classification adapted to SWAT by Chea (2012). Climate data consist in daily time-step measurements from 12 Météo-France (French weather forecasting agency) stations (Fig. 1), from January 1997 to December 2010.

2.3.2. Hydrological data

Monthly stream flow data from six selected gauging stations along the river continuum were used to calibrate the model: Saint-Béat, Foix, Valentine, Roquefort, Auterive and Portet (Fig. 1). This selection was intended to represent the topographic diversity of the catchment – some are located in the mountain range and others in the plain. Some of those stations are present on the Garonne River (Saint-Béat, Valentine, Portet) while others are on its main tributaries: the Salat (Roquefort) and the Ariège Rivers (Foix and Auterive). The aim was to perform a calibration along the river continuum. Data originate from the *Banque Hydro* national database and cover the period from 1997 to 2010. The only data missing over this period are: December 2008 for the

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Table 2
Statistics on elevation (m), including snow dominated subbasins (grey) (locations are given in Fig. 1).

Subbasin	Elevation				Subbasin	Elevation			
	Min	Max	Mean	Median		Min	Max	Mean	Median
1	140	276	203.9	212	15	195	1597	439.9	386
2	142	286	204.8	207	16	270	1566	499.9	441
3	143	200	163.0	162	17	198	1690	506.5	404
4	154	342	230.9	232	18	197	2317	526.2	400
5	178	362	257.7	260	19	420	2119	957.1	877
6	157	394	242.2	235	20	480	2136	1001.3	960
7	157	587	314.9	317	21	390	2826	1222.5	1117
8	155	798	313.2	287	22	377	2172	873.8	801
9	192	746	360.4	348	23	392	2840	1198.4	1116
10	265	503	315.0	297	24	419	3139	1485.2	1459
11	264	539	389.0	386	25	480	3146	1536.9	1517
12	319	567	384.8	368	26	471	3086	1702.6	1709
13	360	710	456.9	438	27	473	2886	1532.0	1555
14	322	2102	760.3	633	28	503	2928	1721.1	1775

Table 3
Data sources.

Data type	Data source	Scale
DEM	NASA/METI (ASTER, 2011)	Grid cell 90 m × 90 m
Land use	Corine Land Cover (CLC, 2006)	1:100,000
Soil	European Soil Database (ESDB, 2006)	1:1,000,000
Climate	Météo-France (https://donneespubliques.meteofrance.fr/)	
River discharge	Banque Hydro (http://www.hydro.eaufrance.fr/)	
Snow cover area	National Snow and Ice Data Center (NSIDC)	Grid cell 500 m × 500 m

Valentine station and July to November 2000 for the Auterive station.

2.3.3. Snow covers data: MODIS and in situ data

Snow cover area data were extracted from the MOD10A2 product version 5 (Hall et al., 2006). MOD10A2 provides syntheses of the maximum snow extent over a compositing period of eight days from February 2000 to the present. For each pixel, MOD10A2 indicates whether snow was detected at least once over a period of eight days (snow presence or absence). This product is generated using observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) on board NASA's Terra satellite. The original grid spatial resolution is close to 500 m. The MOD10 series snow products have been extensively validated in various environments, including mid-latitude mountainous areas (Hall and Riggs, 2007). MOD10A2 is well suited to hydrological studies because most of the cloud-covered pixels are eliminated by the compositing procedure (Magand et al., 2013). However, cloud-covered pixels will remain in the MOD10A2 synthesis whenever clouds persist more than eight days. Missing data have been interpolated in order to allow a direct comparison with the model output as described in Gascoin et al. (2015).

MOD10A2 tiles over the Pyrenees were first assembled and reprojected in the Lambert-93 reference system at 500 m resolution using the nearest-neighbour option in the MODIS Reprojection Tool (Dwyer and Schmidt, 2006). A simple gap-filling algorithm adapted from Parajka and Blöschl (2008) was then applied to interpolate the remaining pixels obstructed by clouds. The algorithm works in three sequential steps: (i) spatial filter: each cloud pixel is reclassified as snow (no snow) if at least five of the eight adjacent pixels are classified as snow (no snow); (ii) temporal filter: a cloud pixel is reclassified as snow (no snow) if the same pixel is classified as snow in both the preceding and the following grid (*i.e.* in the previous and the subsequent eight-day syntheses). This temporal filter can be extended to the grids $n+2$ and/or $n-2$ if cloud obstruction persists in grids $n+1$ and/or $n-1$; (iii) the remaining cloud-covered pixels are reclassified on an image basis using a classification tree taking into account four prediction variables derived from the location and the topography (pixel elevation, aspect, northing and easting). The resulting gap-free product was extracted from the seven snow-dominated subbasins of the study area (Table 2) to compute the snow cover area time series at the eight-day time step. However, MOD10A2 data before gap-filling were used for the spatial comparison with the model results (see Section 3.1).

Manual snowpack measurements from six Météo-France sites (Fig. 1) are available from 2000 to 2010 at a daily time step (https://donneespubliques.meteofrance.fr/). They are spread across subbasins 23, 24, and 25. Two monitoring stations at different elevations are present in each of those subbasins. Table 4 provides details of their elevation, location, affiliated subbasin and elevation band numbers.

2.4. Model sensitivity analysis and calibration

Model sensitivity analysis and calibration were performed for three SWAT projects. The *reference project* uses standard parameters and default values for the snow parameters (and no elevation bands). These parameters are then passed to the following two projects. The *snow parameters project*, as suggested by its name,

Table 4
Snow monitoring information.

Station name	Elevation (m)	Lat	Long	Subbasin	Band
Aulus les Bains	733	42°48′N	1°20′E	23	2
Port d'Aulas Nivose	2140	42°46′N	1°07′E	23	8
St Lary Soulan	827	42°49′N	0°19′E	24	2
Eget	1016	42°47′N	0°16′E	24	3
St Paul d'Oueil	1115	42°50′N	0°33′E	25	3
Maupas-Nivose	2430	42°43′N	0°33′E	25	8

Table 5
Parameters considered for the sensitivity analysis.

Parameters	Description	Min	Max	Default
Hydrological parameters				
EPCO	Plant uptake compensation factor	1	0	1
SURLAG	Surface runoff lag time	0.5	1	4
GW_Delay	Groundwater delay	0	500	31
GW_Revap	Groundwater "revap" coefficient.	0.02	0.2	0.02
GWQMN	Threshold in the shallow aquifer for return flow to occur	0	5000	1000
GWHT	Initial groundwater height	0	25	1
GW_SPYLD	Specific yield of the shallow aquifer	0	0.4	0.003
SHALLST	Initial depth of water in the shallow aquifer	0	50,000	500
DEEPST	Initial depth of water in the deep aquifer	0	50,000	1000
ALPHA_BF	Base flow alpha factor (days)	0	1	0.048
REVAPMN	Threshold in the shallow aquifer for "revap" to occur	0	500	0
RCHRG_DP	Deep aquifer percolation fraction	0	1	0.05
ESCO	Soil evaporation compensation factor	0	1	0.95
CN2 (relative test)	SCS runoff curve number	−0.2	0.2	HRU
CANMX	Maximum canopy storage	0	100	HRU
OV_N	Manning's "*n*" value for overland flow	0.01	30	HRU
SOL_AWC (relative test)	Available water capacity of the soil layer	−0.5	0.5	Soil layer
SOL_K (relative test)	Saturated hydraulic conductivity	−10	10	Soil layer
SOL_Z (relative test)	Depth from soil surface to bottom of layer	−500	500	Soil layer
EVRCH	Reach evaporation adjustment factor	0.5	1	1
EVLAI	LAI at which no evaporation occurs from water surface	0	10	3
Snow parameters				
SFTMP	Snowfall temperature	−10	10	4.5
SMTMP	Snowmelt base temperature	−10	10	4.5
TIMP	Snowpack temperature lag factor	0	1	1
SMFMX	Maximum melt rate for snow during year (summer solstice)	0	20	1
SMFMN	Minimum melt rate for snow during year (winter solstice)	0	20	0.5
SNOW50COV	Snow water equivalent that corresponds to 50% snow cover	0	1	0.5
SNOWCOVMX	Snow water content that corresponds to 100% snow cover	0	100	1
SNO_SUB	Initial snow water content	0	300	0
Elevation band parameters				
TLAPS	Temperature lapse rate	−10	10	−6
PLAPS	Precipitation lapse rate	−100	500	0
SNOEB	Initial snow water content in elevation bands	0	300	0

identifies the snow parameters but not the elevation band parameters. Finally, the *elevation bands project* adds ten elevation bands to the snow-dominated subbasins.

Sensitivity analysis and calibration were undertaken by SWAT-Cup (Abbaspour, 2013), and its SUFI-2 algorithm (Abbaspour et al., 2004). SWAT-Cup is an external software tool allowing SWAT users to realise automatic calibration with more comfort and efficiency, which has been used increasingly by the SWAT community (Arnold et al., 2012). In SWAT-Cup, users have the option between different calibration algorithms of which SUFI-2 is known to achieve a good calibration performance in a limited number of iterations (Yang et al., 2008).

A large number of parameters may be calibrated through SWAT-Cup, making SWAT a very adaptive model. Only a subset of them may actually be selected for a sensitivity analysis. In this study, the initial parameter selection was interpreted on previous SWAT modelling across the Pyrenees and the Garonne watershed (Boithias, 2012; Chea, 2012; Oeurng et al., 2011; Pinglot, 2012).

The sensitivity analysis methodology follows the one-at-a-time procedure proposed in Abbaspour (2013). This procedure tests SWAT sensitivity to changes in a parameter, when all other parameters are kept constant. Sampling relies on the latin hypercube method (McKay et al., 1979) in order to cover all the domain of variation of the parameters, dividing the user-defined ranges into several subranges of equal probability. In all, 32 parameters were considered (Table 5): 21 hydrological parameters for the reference project, 8 for the snow parameters project and 3 for the elevation bands project. Five runs were performed over the ten-year period from 2000 to 2010, preceded by a three-year warming period (1997–2000).

Table 6
Influential parameters.

Hydrological parameters		Snow parameters		Elevation band parameters
GW_Delay	RCHRG_DP	SMFMX	SMTMP	TLAPS
GW_Revap	ESCO	SMFMN	TIMP	PLAPS
GWQMN	CN2	SNOW50COV		
ALPHA_BF	CANMX	SNOWCOVMX		
REVAPMN	SOL_AWC	SFTMP		

Once sensitive parameters have been identified, a 1500-run calibrations, as recommended in Yang et al. (2008), were performed three time (one for each project), for the six gauging stations identified in Fig. 1. SWAT-Cup allows the user to select subbasins for calibration. In order to avoid possible conflict caused by the use of hydrologically-connected gauging stations, three groups of subbasins were created. Parameters were thus identified in three steps from upstream to downstream, leading to different values for each group. Group 1 included subbasins upstream of Saint-Béat, Roquefort and Foix; Group 2 included the remaining subbasins upstream of Portet: Valentine and Auterive; Group 3 is the outlet of the catchment: Portet. Snow parameters for the other two projects were identified in a second step, but at catchment scale, using all six gauging stations simultaneously. Elevation band parameters were finally identified, at subbasin scale, for snow-dominated subbasins (Table 2), using all six gauging stations simultaneously. Calibration and performance criterion calculations have been performed without regard to missing data, as allowed by SWAT-Cup. For each gauging station, calibration was conducted using the Nash–Sutcliffe criterion (NS) (Nash and Sutcliffe, 1970) as the objective function. This metric is normalized in order to allow comparing between the variance of the observed dataset and the existing residual variance between this same observed dataset and the simulated one. NS ranges from $-\infty$ to 1 and is sensitive to large errors. The NS equals 0 when the model is as accurate as the mean of the observed data set and NS equals 1 when the model offers a perfect fit. After calibration, performance was also evaluated based on the percent bias (Pbias). This second metric measures the average bias existing between simulated and observed data. It is given as a percentage. A negative value indicates underestimation while a positive value indicates overestimation. Bias is nil when Pbias equals 0.

2.5. Validation of snow simulation

MODIS and *in situ* data are only used for validation. Neither of them can be used for calibration. SWAT computes snow water equivalence – discretised or not by elevation band – when MODIS detects the presence of snow in term of surface and *in situ data* would have required a very dense spatial density for calibration, which is not available.

After calibration, MODIS and the observed snow data were used to validate SWAT snow simulation. Simulated spatial and temporal series were compared to MODIS data and temporal series to *in situ* snowpack observations.

Spatial analysis compares snow presence and absence for specific days: during the maximum extent of the snow period and at the end of the snow period, when the snow is melting and its extent reduced, *i.e.* around mid-February for the maximum extent and in May for the end of the melting period. The MODIS detection level was estimated to be about 15 mm of snow water equivalent (SWE) following Klein and Barnett (2003). Accordingly, the presence of snow in SWAT maps was confirmed only for simulated SWE above 15 mm, based on the average value for all HRUs present per elevation band.

Temporal analysis was performed on each snow-dominated subbasin, comparing SWE in two different ways: MODIS and manual observations. For MODIS, the validation was undertaken at subbasin scale, by averaging daily SWE values of all bands on every subbasin over the entire simulation period. For the *in situ* observation, validation was performed at the station scale. Since only the snowpack depth was actually measured, snowpack densities between 0.2 and 0.45, typical of the Pyrenees (Fassnacht et al., 2010; Lopez-Moreno et al., 2013), were explored to allow a comparison of SWE and SWAT outputs.

3. Results

3.1. Model performance

The sensitivity analysis identified the most influential parameters for each project (Table 6) from the initial list given in Table 5. Ten of the twenty-one hydrological parameters influence the variance of the first SWAT project, while the majority of the snow

Table 7
Calibrated values for each project.

Parameters	Calibration range	Calibrated values Subbasins calibrated Group 1	Group 2	Group 3
Reference project				
CN2.mgt (relative from HRU values)	−0.1/+.01	+0.065	−0.020	−0.06
SOL_AWC.sol (relative from Soils layers values)	−0.05/+0.05	−0.038	−0.042	−0.004
GW_DELAY.gw (relative from default values = 31)	−30/60	4.63	87.19	22.15
GWQMN.gw (relative from default values = 1000)	−500/500	1033.67	806.33	679.00
GW_REVAP.gw	0.02/0.2	0.10	0.12	0.03
RCHRG_DP.gw (relative from default values = 0.05)	−0.04/0.04	0.04	0.05	0.04
ALPHA_BF.gw	0/1	0.23	0.25	0.75
REVAPMN.gw	0/1000	467.00	449.67	583.00
CANMX.hru	0/30	16.81	19.57	0.39
ESCO.hru	0.5/0.95	0.56	0.80	0.85

Parameters	Calibration range	Calibrated values Subbasins calibrated All (catchment scale)
Snow parameters project		
SFTMP.bsn	−2/2	1.30
SMTMP.bsn	−2/2	1.97
SMFMX.bsn	2/6	4.96
SMFMN.bsn	2/6	3.16
TIMP.bsn	0/1	0.14
SNOCOVMX.bsn	0/50	38.38
SNO50COV.bsn	0.3/0.7	0.50

Parameters	Calibration range	Calibrated values Subbasins calibrated All (catchment scale)	Snow dominated subbasins
Elevation bands project			
SFTMP.bsn	−2/2	1.52	
SMTMP.bsn	−2/2	−0.49	
SMFMX.bsn	2/6	3.05	
SMFMN.bsn	2/6	5.84	
TIMP.bsn	0/1	0.54	
SNOCOVMX.bsn	0/50	29.48	
SNO50COV.bsn	0.3/0.7	0.64	
TLAPS.sub (Relative from default values = −6)	−2/2		−0.61 (=−6.61)
PLAPS.sub (Relative from default values = 200)	−100/500		+423.40 (=623.40)

Table 8
Calibration performance: NS and P-bias for each gauging station at a monthly time step and for each calibration project: reference, snow parameters and elevation bands projects.

	Reference project		Snow parameters Project		Elevation bands project	
	NS	P-Bias (%)	NS	P-Bias (%)	NS	P-Bias (%)
Saint Béat	0.18	4.4	0.24	22.3	0.48	−15.1
Foix	0.14	37.4	−0.16	56.5	0.61	25.7
Roquefort	0.67	16.7	−0.03	57.8	0.69	0.2
Valentine	0.3	−15	0.75	1.4	0.28	−34.2
Auterive	−0.17	56.2	−0.46	66.5	0.18	46.3
Portet	0.21	47.3	0.57	34.5	0.88	1

and elevation band parameters are also retained for the same reasons.

Calibrated values for each group of subbasins created for the abovementioned reasons are presented in Table 7.

The results associated with each project are illustrated in Table 8. The performance of the *reference project* is poor overall: the mean NS criterion for monthly discharge reaches only 0.22, while Pbias is 24.5%. Only one gauging station has NS higher than 0.5. Retaining those calibrated hydrological parameters and identifying snow parameters (snow parameters project) worsened performance: a mean NS of 0.15 and Pbias of 39.83%. Even though NS improved at the final outlet (Portet), seeking snow parameters that are valid for all mountainous elevations proved to be difficult, if not impossible. Indeed, results for some stations are improved (Valentine, Portet) while others are worse (Roquefort, Auterive), creating inconsistency in performance at catchment scale. Pbias followed a similar trend, since only Valentine and Portet improved compared with the reference project. On the other hand, the elevation bands project led to a better performance: mean NS of 0.53 and Pbias of 3.98. Performances in terms of NS are now more consistent with the ones in the reference project. Except for Valentine, all gauging stations improved in performance. It is also noteworthy that the improvement is not only limited to the snow-dominated subbasins, but is also transmitted down to the outlet of the catchment (Portet), located tens of kilometres into the plain and where the largest gain in realised: NS of 0.88 instead of 0.21 and Pbias of 1 instead of 47.3.

3.2. Snow simulation

Streamflow simulation is improved introducing elevation bands to the model setup. This study tries to go further by considering the temporal evolution of the simulated snow cover. The latter was assessed comparing SWAT outputs to MODIS data at 10 February 2005, which roughly corresponds to the maximum snow cover (Fig. 2A), and at 10 May 2005, which is typical of the end of the snow season (Fig. 3B).

SWAT snow cover in Fig. 2A is fairly consistent with MODIS data, especially for subbasins 21 and 26. It is somehow underestimated in subbasins 27, 24, and 25 and overestimated in subbasin 23 where the largest disparity is noticed. On the other hand, SWAT melting lags MODIS data in Fig. 2B, but snow is then limited to the

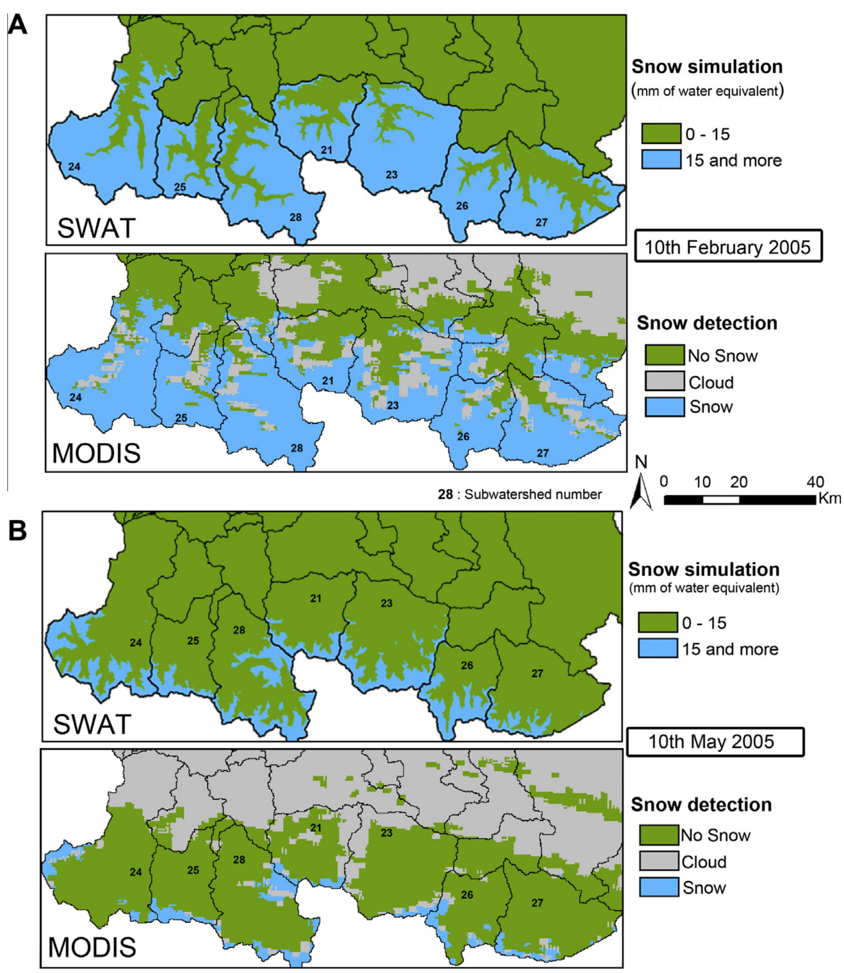

Fig. 2. Snow comparison: (A) 10 February 2005 and (B) 10 May 2005.

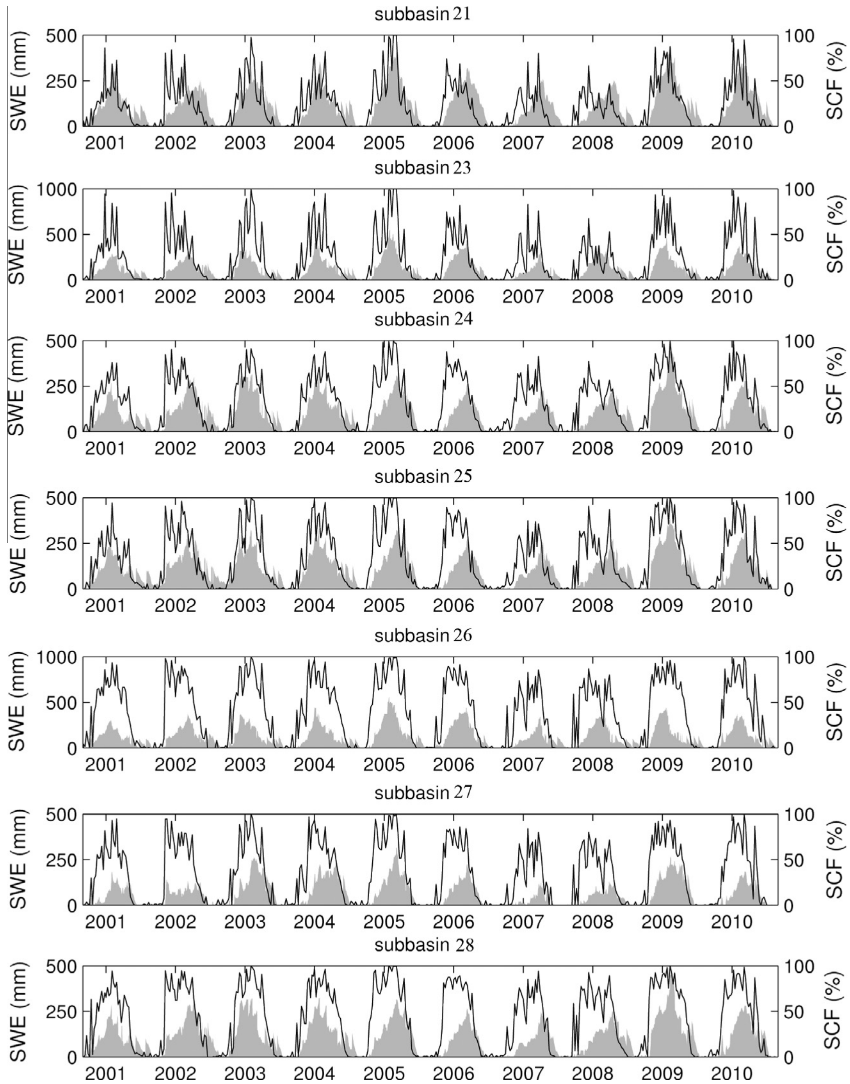

Fig. 3. Temporal snow comparison. Solid black line represents the daily percentage of snow cover detected by MODIS at subbasin scale, while the grey surface is SWAT snow water equivalent.

mountain tops. Overall representation of snow in Fig. 2B is slightly overestimated by SWAT. Subbasins 27 and 24, where snow is underestimated during snow season, improve during the melting period.

The previous analysis was complemented by a time-series comparison of the MODIS percentage of snow cover and SWAT snow water equivalent for the entire ten-year period. Fig. 3 illustrates the extent of snow cover period. The MODIS data depict the surface area covered by snow, while SWAT provides snow water equivalent values. For most years and subbasins, SWAT and MODIS snow season begins simultaneously, even if a delay is noticeable for SWAT in 2005 or 2007 and for some subbasins in 2006. There is less agreement at the end of the snowmelt period, when SWAT maintains snow longer than that reported by MODIS data, as in Fig. 2. The peak of the snowpack also occurs later for SWAT than for MODIS.

A comparison was also carried out between SWAT snow water equivalent and a range of snow water equivalent values calculated from the snowpack depth time series (2000–2010). However, for the sake of clarity, the analysis presented here focused on the 2004–2005 snow accumulation and melting periods, which offered the widest spatial coverage – in practice, only the *Maupas-Nivose* site is affected by missing data, so 2003–2004 is used at that site instead. As a first step, Fig. 4 compares SWAT snow outputs for the elevation bands to which the stations belong, and to the upper or lower bands for completeness.

The comparison reveals the altitudinal distribution of the snow water equivalent within SWAT. Simulations for the highest sites, Port d'Aulus Nivose and Maupas Nivose (elevation band 8), overestimate the snowpack while lower elevation bands offer a closer fit to the observations. The same discrepancy occurs for the lower stations (Aulus-les-Bain, Saint Larry Soulan, Eget, Saint Paul d'Oueil) where higher bands offer a better agreement to the observations. These findings are consistent with the previous spatial and temporal analyses.

4. Discussion

4.1. Model sensitivity analysis and calibration

Parameters deemed influential by the sensitivity analysis are consistent with those of other studies, particularly Stratton et al. (2009) where sensitivity is explored in the context of water budget under snow influence. The two main differences concern ground water delay and maximum canopy storage. Ground water delay

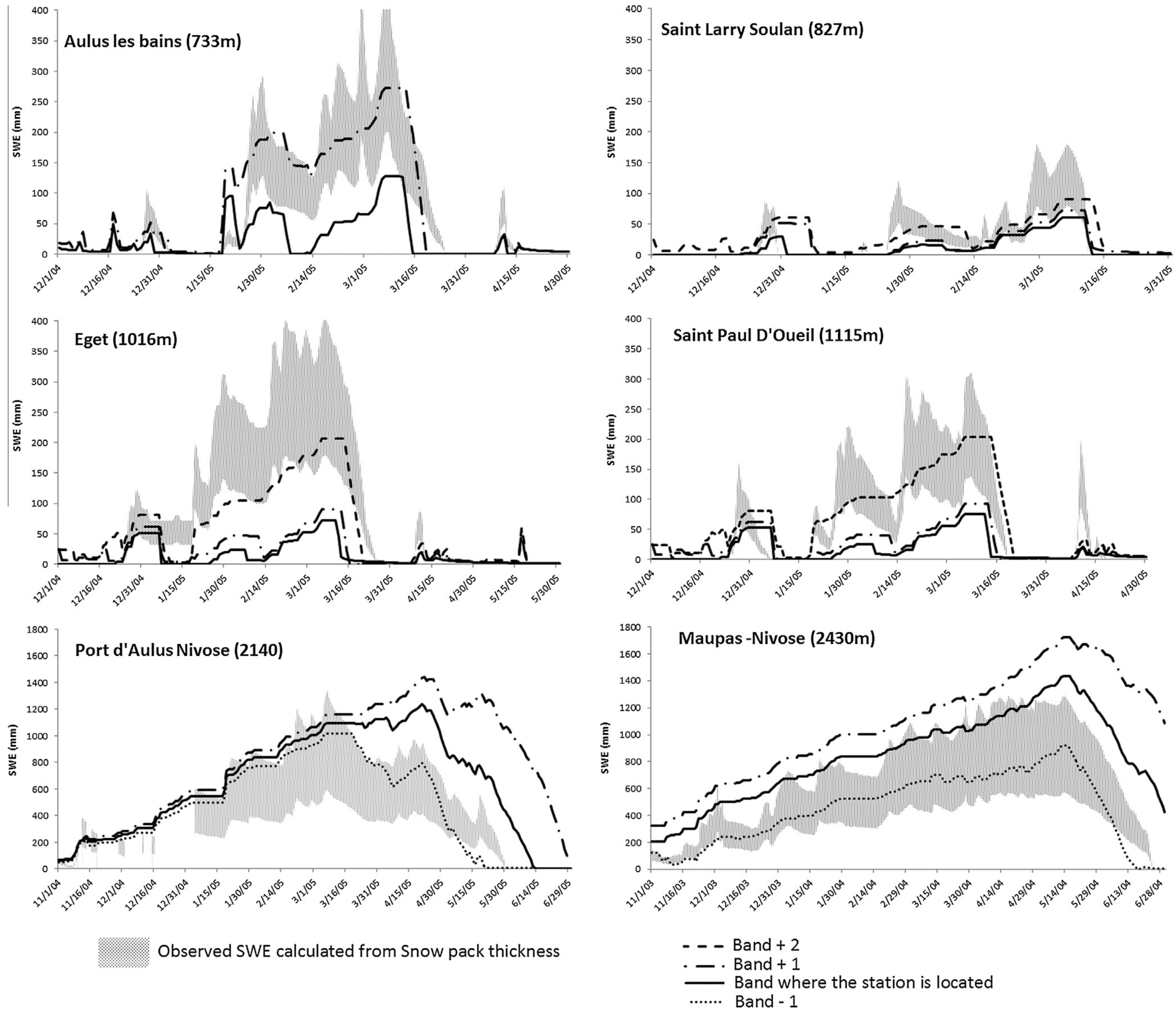

Fig. 4. Snow water equivalent comparison between SWAT and a range of possible values calculated from observations.

(GW_DELAY) is lower in the upper part of the catchment because of its altitudinal soil structure and slope that favour water circulating faster than in the plain. The presence of a dam upstream of the Valentine gauging station may also provide an explanation. For the same reason, canopy storage (CANMAX) differs since the upper part is mostly forested and the lower parts foster agricultural grassland and fields.

Important similarities between parameters considered as sensitive can also be observed in Palazón and Navas (2014). In this work, conducted over a proximal watershed on the Spanish side of the Pyrenees, sensitive parameters related to groundwater circulation and snow are identical. The only difference is this initial volume of water in the aquifers, which are not considered sensitive in our case, as regard of the 3 years warmup period performed.

Only two elevation band parameters are non-influential: the initial water content parameters SNO_SUB and SNOEB. Insensitivity may originate from using a three-year warming period, which diminishes their influence on the variance of the model outputs by balancing this reservoir before the first year of simulation. Differences between the *snow parameters project* and *elevation bands project* culminate in the snowpack lag factor (TIMP) and snow melt temperature (SMTMP). In the *snow parameters project*, SMTMP appeared slightly too high (1.97 °C), but the use of elevation bands reduced it to a more likely value (−0.49 °C). PLAPS and TLAPS calibrated value are consistent with values used by Palazón and Navas (2014) where TLAPS values is set to −5.0 °C/km and PLAPS is set to values between 550 and 1000 mm/km depending on the watershed considered.

The performance of the reference project stresses the possible drawbacks of calibrating a project when only the upper part of the catchment is snow dominated. Improving the simulation identifying snow parameters at basin scale is not very effective either. However, identification of the elevation band parameters clearly improved the performance, not only for the snow-dominated subbasins, but also for the plain downstream.

4.2. Validation of snow simulation

SWAT elevation bands improve hydrological performance and lead to plausible snowpack simulations. Highlights of some elements of the analysis are summarized below:

First, comparison of snow simulations, with *in situ* data revealed a non-homogeneous error: snow is overestimated in higher elevations and underestimated in lower ones. The fact that the error is not a function of altitude impedes any improvement based on linear temperature or precipitation lapse rates alone. As underlined by many authors, *e.g.* Kirchner et al. (2013) and Minder et al. (2010), orogenic lapse rate is a complex phenomenon, highly dependent on local topographic factors, such as valley shapes, seasonal variations, and temporal phenomena such as temperature inversion and foehn wind. Rijckborst (1967) analysed precipitation measurements over the upper part of the Garonne – corresponding to subbasin 28 in Fig. 1 – and found lapse rate from 340 to 880 mm/km/year. Castellani (1986) in northern Alps, founds that area judged as homogeneous in terms of precipitation, lapse rates from 200 to 600 mm/km/yr. Hence, the identification of a single temperature and precipitation lapse rates over large watersheds will inevitably lead to errors. Winter temperature inversion is also a common phenomenon across the Pyrenean area (Pagès and Miró, 2010; Pepin and Kidd, 2006). It could lead to a reduction in snowfall uphill and an increase downhill, which is consistent with the SWAT snowpack simulation error.

Second, a consequence of the overestimation in higher elevations, the snow cover area near the end of the melting period and the snowmelt duration are also overestimated. However, SWAT could only compute snow on each elevation band – a finite entity – which is restrictive. Elevation bands represent, in some way, the maximum spatial resolution of the model. Snow in the higher parts of subbasins is definitely a sensitive part of the computation process, which specifically could require more resolution. On the basis of that assessment, two options appear feasible: modify the SWAT model to compute more bands, thereby increasing the model resolution, or use the ten bands already available differently, by not setting them up regularly from top to bottom, but with thinner bands in the upper part. However, the present study deals with bands that are set up using an equal elevation fraction (10%) and does not test snow simulation driven by computation using bands of an equal area fraction. By using irregularly spaced elevation bands with thinner bands at higher altitudes, covering a smallest surface and elevation range, resolution in the higher elevation will be increased. As SWAT uses the mean elevation in each band to compute the change in temperature and precipitation, the increased elevation range represented by upper bands could reduce the overestimation observed in the present study. Weather data are also essential parameters in the snow simulation process. This study was developed using 12 different weather stations (Fig. 1), which is a substantial number for this 9200 km^2 catchment in comparison to other successful studies (Bieger et al., 2014; Stehr et al., 2009). Moreover, data from each station can be considered reliable, with the mean rate of missing values over the simulated period being 0.25% for temperature data and 0.5% for precipitation data.

Finally, scarcity of reservoir management data doesn't seem to be determining in the snow dynamics simulation, even after calibration process. When comparing subbasins affected by reservoir management, particularly for subbasin 26 and 27, which were found to be the most impacted during winter (Sauquet et al., 2010), and non-impacted subwatershed (21, 23, and 28), no substantial difference can be detected between snow simulation error time series, after validation with the MODIS data.

4.3. Impact on the hydrological cycle

Modifications in snow dynamics will drive changes in SWAT water partitioning at subbasin scales.

Introduction of elevation bands and their associated parameters, such as the precipitation lapse rate, change the estimated volume of precipitation received by each subbasin. Table 9 highlights this variation from one SWAT project to the others. Changes are substantial for subbasins 27 and 21 in which the increase of annual precipitation volume is more than 50% – note than both subbasins underestimated the mean annual precipitation when simulated without elevation bands. This may result from the use of a unique weather data for the entire subbasins and from station site elevation much closer to the valley than to the mountain peaks. For instance, subbasin 21 relies only on the St Giron weather station (elevation of 414 m) when the subbasin elevation varies from 390 to 2826 m, leading to a possibly wrong total precipitation. On the other hand, precipitation lapse rates were calibrated here from seven snow-dominated subbasins and may not be pertinent for neighbour subbasins. This is likely the case for subbasin 23 where an overestimation of snow cover extent has been detected.

Table 9
Mean annual precipitations (mm/year) for hydrologic years (from September to August) over 2000–2010 for each snow dominated subwatershed. A = Reference project; B = Snow parameters project; C = Elevation bands project.

Subwatersheds	28	27	26	25	24	23	21
A/B	1558	876	1625	1558	1558	1625	918
C	1845	1372	2292	1904	1885	2188	1528
Var %	+18	+57	+41	+22	+21	+35	+66

The presence or absence of snow cover will also strongly affect the water balance. Therefore, it differs from one project to the others, especially runoff, infiltration and actual evapotranspiration (AET), allowing more water to be stored in the watershed as snow and soil moisture. Table 10 illustrates differences in the annual water partitioning for each subbasin. AET is the main water flux before introduction of elevation bands on the model set up. When using elevation bands, fraction of annually evapotranspirated water decrease. Infiltration then becomes the main water flux along with runoff.

No field data are available for comparison, but values of water partitioning obtained from the elevation bands project are more consistent with previous studies over similar snow-dominated subbasins. Etchevers (2000), using the ISBA-CROCUS model over some snow-dominated alpine watersheds, found a AET fraction ranging from 24.1% to 35.8%, infiltration from 50% to 57%, and runoff from 11.5% and 21.3%. Habets et al. (1999) obtained similar result when studying the Upper Rhône watersheds: an AET of about 25%. Habets et al. (2008), at national scale, find for most part of our catchment, an annual mean ratio of evaporation to precipitation lower than 0.25.

Changes in annual values are mainly due to modification of the snow cover dynamics and present a great level of disparity depending on seasonality.

Fig. 5 illustrates differences between each project at a monthly time step. Strong seasonal differences appear: the presences of a spring snow cover on the upper part of the watersheds influence clearly the ratio between infiltrated and evapotranspirated water. In SWAT, when a snow cover is present, melt water is added to the precipitation and partitioned between only runoff and infiltration (evaporation is automatically excluded). Sublimation of snow is included in the AET calculations, but its impact appears limited on the global balance. The decrease in air temperature that results from the use of elevation bands will also be detrimental to AET over the year.

As suspected, modifications in the upper part of the subbasins change the hydrological behaviour from upstream to downstream. As discussed in Section 3.1, a better representation of the snow related processes have allowed simulation improvements. For instance, Fig. 6 details the hydrograph for each gauging station and project.

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Table 10
Water partitioning within snow-dominated subbasins. Mean annual data over 2000–2010 (hydrologic years from September to August).

Subwatershed		28	27	26	25	24	23	21
Reference project								
Precipitation	**mm**	**1558**	**876**	**1625**	**1558**	**1558**	**1625**	**918**
Evapotranspiration	mm	822	662	878	813	792	982	817
	%	53	76	54	52	51	60	89
Runoff	mm	346	66	338	192	318	169	62
	%	22	8	21	12	20	10	7
Infiltration	mm	389	148	408	552	448	474	39
	%	25	17	25	35	29	29	4
Snow parameters project								
Precipitation	**mm**	**1558**	**876**	**1625**	**1558**	**1558**	**1625**	**918**
Evapotranspiration	mm	768	602	858	753	746	952	811
	%	49	69	53	48	48	59	88
Runoff	mm	351	73	341	201	320	176	63
	%	23	8	21	13	21	11	7
Infiltration	mm	439	200	427	603	491	497	44
	%	28	23	26	39	32	31	5
Elevation bands project								
Precipitation	**mm**	**1845**	**1372**	**2292**	**1904**	**1885**	**2188**	**1528**
Evapotranspiration	mm	435	473	370	285	353	378	309
	%	24	35	16	15	19	17	20
Runoff	mm	619	226	759	410	599	441	359
	%	34	16	33	22	32	20	24
Infiltration	mm	791	672	1162	1210	932	1369	860
	%	43	49	51	64	49	63	56

Water partitioning within snow-dominated subbasins. Mean annual data over 2000–2010 (hydrologic years from September to August) for evapotranspiration, runoff and infiltration fluxes, compared to precipitation (Bold values).

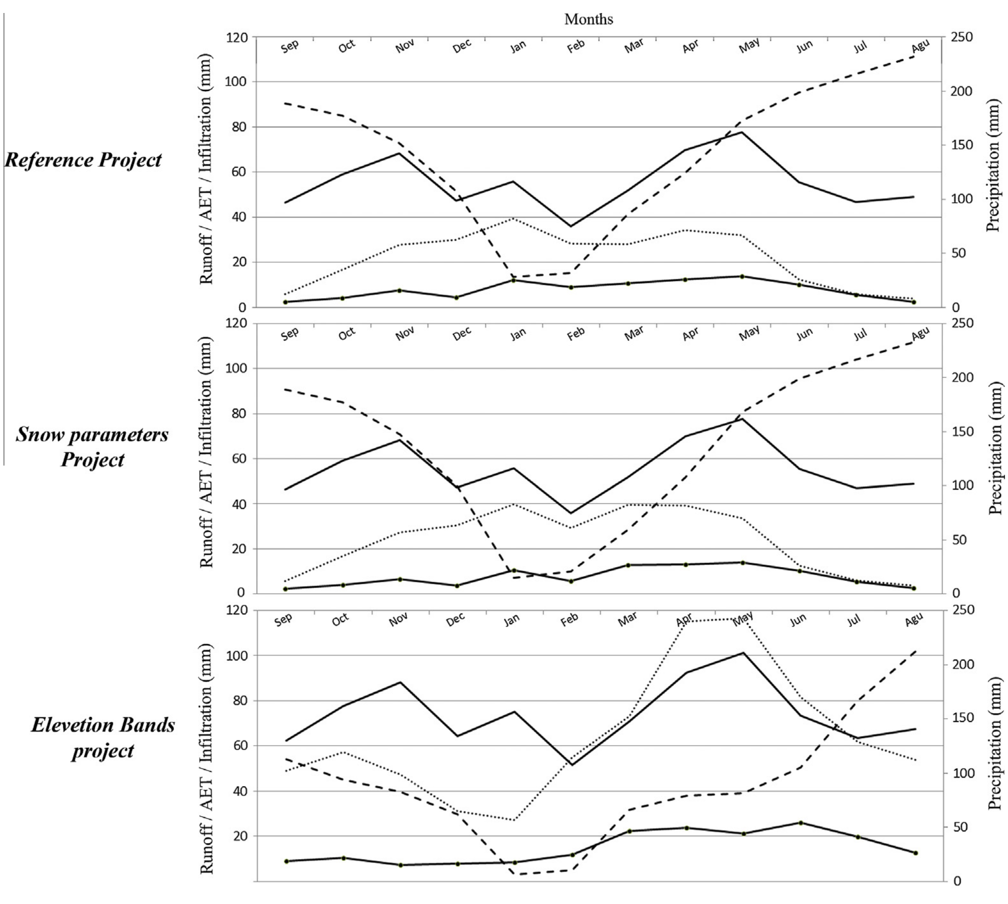

Fig. 5. Monthly mean values of snow dominated subwatersheds over 2000–2010.

As suggested by the improvement in performance, hydrographs from the elevation band project provide a better fit to the observed values, mainly for high flows in spring and summer – excluding Auterive gauging station which flows are underestimated in all three projects. The reference project produces high flow peak that are well synchronised with the observations but that

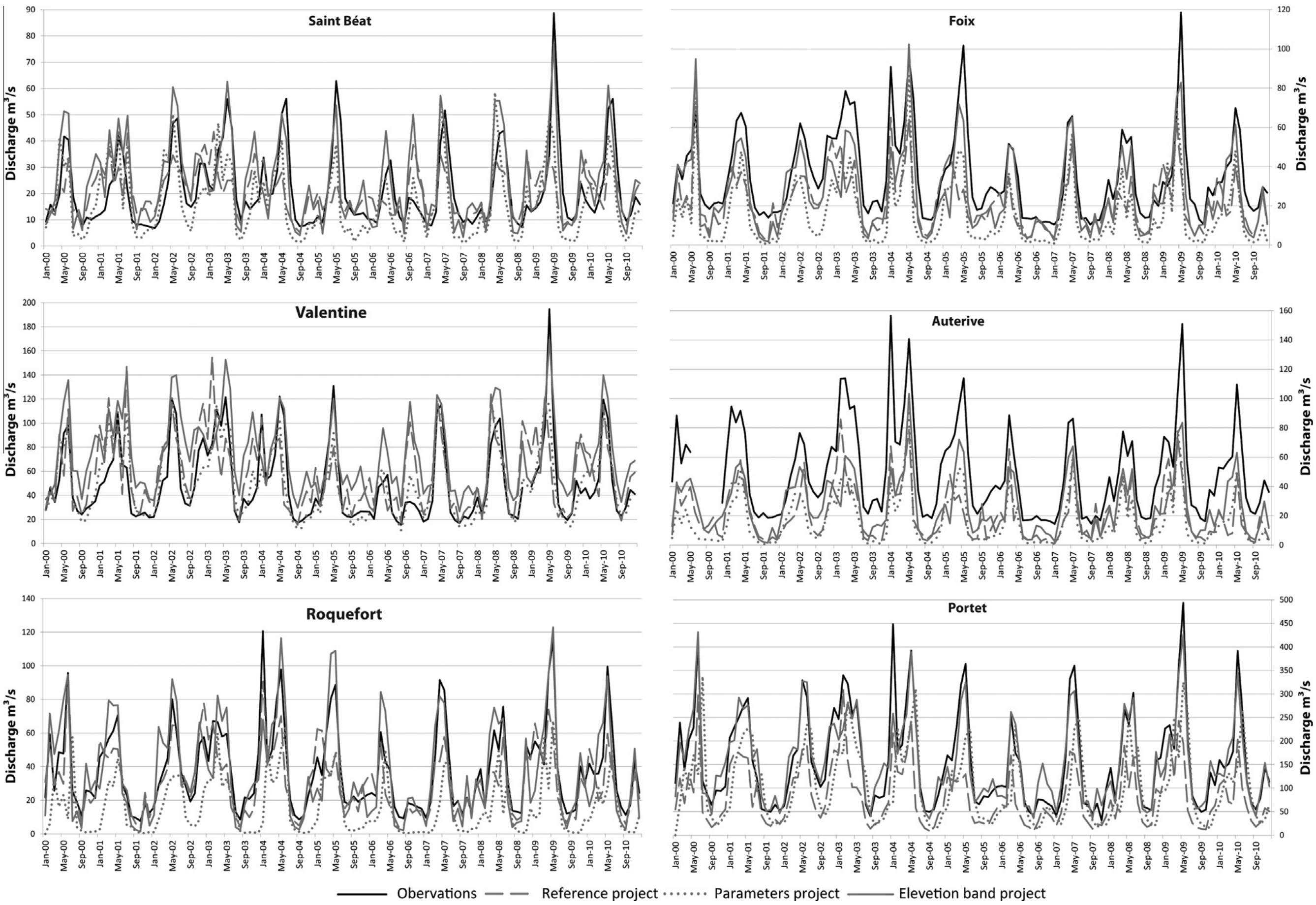

Fig. 6. Hydrographs for the 6 gauging stations.

underestimates them notably. The snow parameters project most of the time performs better in term of magnitude but not in terms of synchronicity.

Low flows are not improved by introducing elevation bands. Dessens and Bücher (1997) highlighted that the Pyreneans precipitation lapse rate varies seasonally: it was found twice more important in winter than in summer. Introduction of a yearly homogenous lapse rate, as in SWAT, may thus lead to hydrological modelling errors.

5. Conclusion

Comparison of three calibration projects revealed that the implementation of elevation bands and their associated altitudinal lapse rates had a positive impact on the hydrological simulation of the Upper Garonne watershed. Without elevation bands, the identification of snow-related parameters alone failed to improve the reference project notably. In fact, it turned out somehow detrimental, producing gains at some sites but losses at others. The positive impact of the elevation bands cascaded downstream (large improvement at Portlet), which is extremely positive for the modelling of the whole watershed. In accordance with Zhang et al. (2008), this conclusion emphasises the importance of spatially detailed snow computation.

The accuracy of SWAT snow simulations was compared with MODIS and snowpack depth data. The former confirmed the reasonably good quality of the SWAT spatial representation of the snow presence, despite the lack of reservoir management data insofar as those reservoirs are mostly used for low flow support. However, SWAT also slightly overestimated the snow cover at the end of snow season and delays the snow water equivalent peak and the end of the snowmelt. Comparison with the snow depth time series revealed that SWAT overestimates snow water content in higher elevations and underestimates it in lower ones. Overestimation of snow in term of extent and timing at the end of the snowmelt is directly related to the overestimation of snow water content in the upper elevation bands.

Increases in annual precipitation induced by a linear and yearly homogenous precipitation lapse rate calibrated over the overall watershed revealed the limits of SWAT dealing with the spatial (nonlinearity in terms of elevation) and temporal variabilities (variation over the year). Inclusion of lapse rates influenced the water partitioning in snow-dominated subbasins. The runoff and infiltration increase across affected subbasins, when evapotranspiration decreases under the effect of a snow cover. Water budget computed by the elevation band project turned out more in accordance with similar findings on other catchments. Stream flows are also improved by elevation bands. Simulated high discharge peaks, supported by a larger groundwater contribution and a more persistent snow cover, are time-shifted and their amplitude extended.

The importance of snow simulation processes and associated parameters has been highlighted. Even though snow-dominated areas represented just a portion of the catchment, it is beneficial to use elevation bands. This enhancement echoes the ability of SWAT in representing the snow cover. It is recommended to eventually compare the two available definitions of elevation bands in SWAT: area and elevation. This subject will need to be explored in

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further studies in order to test the difference between each option in regard to snow simulation. Beyond those considerations and the reasonably good representation of the snow accumulation and melt obtained in this study, there are still place for further improvements. For instance, lapse rates computations remain problematic because of their spatiotemporal variability. Snow representation could probably be improved if each snow-dominated subbasin could be calibrated individually with a dedicated gauging station and weather station. One may also consider a lapse rate that varies seasonally.

Acknowledgements

Authors acknowledge the financial support given by the Natural Sciences and Engineering Research Council of Canada and the Institut Hydro-Québec en environnement, développement et société. Simon Gascoin was supported by the Pyrenees Climate Change Observatory (OPCC-POCTEFA EFA 235/11). Collaboration with Simon Gascoin was part of the REGARD project (Modélisation des ressources en eau sur le bassin de la Garonne: interaction entre les composantes naturelles et anthropiques et apport de la télédé tection) – RTRA Sciences et Technologies pour l'Aéronautique et l'Espace – 2014-2017.

We sincerely thank Météo-France for meteorological data and AEAG for hydrological discharge data providing.

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Please cite this article in press as: Grusson, Y., et al. Assessing the capability of the SWAT model to simulate snow, snow melt and streamflow dynamics over an alpine watershed. J. Hydrol. (2015), http://dx.doi.org/10.1016/j.jhydrol.2015.10.070