Hydrological modelling in the High Atlas mountains with the help of remote-sensing data: milestones of the SudMed project

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Abstract

The sustainable management of water resources worldwide is one of the most important challenges of the 21st century. In the Tensift-Haouz plain, located in central Morocco and characterized by a semi-arid climate, more than 85% of available water is used for agriculture. Precipitation, which is concentrated over the High-Atlas mountain range, falls in a significant proportion as snow leading to storage in winter followed by snowmelt that contributes to baseflow in the summer.
In order to understand the hydrological cycle of the Tensift basin, the SudMed project has developed a research program based on modelling, experimental and remote-sensing monitoring of the High Atlas subbasins. Top-down and bottom-up strategies have been combined in a modelling approach of medium-range complexity. This approach simulates the largely unobservable subsurface flow processes using input data from the sparse network of climate stations while incorporating as much ancillary available information as possible: noisy streamflow observations, geochemical elements tracing, remotely-sensed land cover and snow area. The bottom-up approach is based on the distributed hydrological model SWAT and an energy balance snowmelt model, while the top-down approach uses two global semi-empirical models, GR4J and SRM.
In parallel, complex energy-balance models are used to ensure realistic outputs for the simple degree day snowmelt models embedded in the three models. Time series of snow cover derived from SPOT-VEGETATION and MODIS are assimilated into all models to improve the contribution of snowmelt to runoff. The improvement is significant given the lack of distributed climate observations, but its impact on the runoff is relatively minor. The spatialisation of the climatological forcing data remains a pitfall for all studies. An improved spatialisation will be developed on the basis of remote-sensing data in the Thermal Infra Red spectrum and outputs of current mesoscale meteorological models, as well as enforcement of geochemical tracing analysis.

Keywords: Morocco, Remote-Sensing, Snowmelt, Climate Change, Hydrological modelling

Introduction

The objective of this study is to understand the hydrological cycle of the High Atlas catchments by use of models and a minimum measurement strategy, with the limitation of scarce historical data (Section 2). Two modelling strategies have been carried out during the SudMed project (Section 3). The first one employs complex models and “first guess” parameterization and spatialisation strategies (“top-down” approach); the second one develops simple models to account for the complexity of the hydrological processes involved in these catchments (“bottom-up” approach). Both strategies have a number of advantages and drawbacks that are depicted in this paper, and have been applied to the available historical dataset. Since the issue is not only to understand the hydrological functioning of the High

Atlas range but also to predict the impact of climate change on its hydrological regime, several additional studies are needed and strategies are finally proposed to fulfil that requirement (Section 4)

1. Context

The Haouz Plain in south-central Morocco is made up of several intensively irrigated districts and is fed by nine head-watersheds located in the High Atlas range. The Atlas range and the Haouz Plain belong to a larger watershed called the Tensift watershed covering 20450 km2 (see Figure 1)*. This region is characterized by scarce water resources and is subject to frequent drought.

During the SudMed project (Chehbouni et al., 2008) one of the nine Atlasic head watersheds, the Rheraya catchment, was selected to study the series of hydrological processes that lead to groundwater recharge in the footplain. This head watershed covers a surface area of about 227 km^2 and is characterized by a semi-arid and mountainous climate. Indeed, the mean measured annual precipitation at the outlet was 363 mm for the period 1971–2002 and the closest meteorological station registered a mean annual potential evapotranspiration of 1073 mm from the Aremd (2000m) between sept. 2003 and sept. 2006. The watershed altitude ranges from 1084 to 4167 m, precipitation occurring as snow in the upper parts of the watershed. Snow is present from November to April on the highest parts. Summer precipitation is mostly convective but cumulative amounts are less than the winter precipitation and wadis can dry out. Rainfall and streamflow data are characterized by high inter- and intra-annual variability, which is typical of semi-arid areas. The average streamflow is 19.3 mm $month^{-1}$, which represents 1.67 $m^3 s^{-1}$. A two- to three-month shift is observed between the pattern of annual rainfall and that of streamflow. This delay characterizes slow flow processes, which can be caused by the existence of different geomorphological units as well as an important groundwater and/or snow component in the water balance.

2. Observation network

2.1. Hydrometeorological network

The High-Atlas range is a very isolated area with very sparse meteorological stations network consisting mostly in one couple of rainfall and streamflow measurements at the outlet of each catchment. Due to the 1995 dramatic storm, the Ourika catchment (506 km^2) next to the Rheraya was equipped with automatic water level sampling and rainfall gauges at three different altitudes. In the Rheraya, daily streamflow and rainfall data is available since 1971 and daily rainfall, snowfall, snow height and air temperature is available at the Club Alpin Français since 1988. During the course of the SudMed project, 2 automatic weather stations were installed at Aremd (2000 m) and Oukaimedem (3250 m) in 2002, and 4 automatic raingauges and air temperature sensors were installed in 2007.
Streamflow measurement is a difficult task in the wadi bed: the gauging frequency (once a month on average) is not always adjusted for quickflow (high flow) occurrence, and wadi beds often undergo drastic modifications after a storm, preventing discharge measurement when the scale is isolated or when the charge-discharge rating curve is no longer valid.

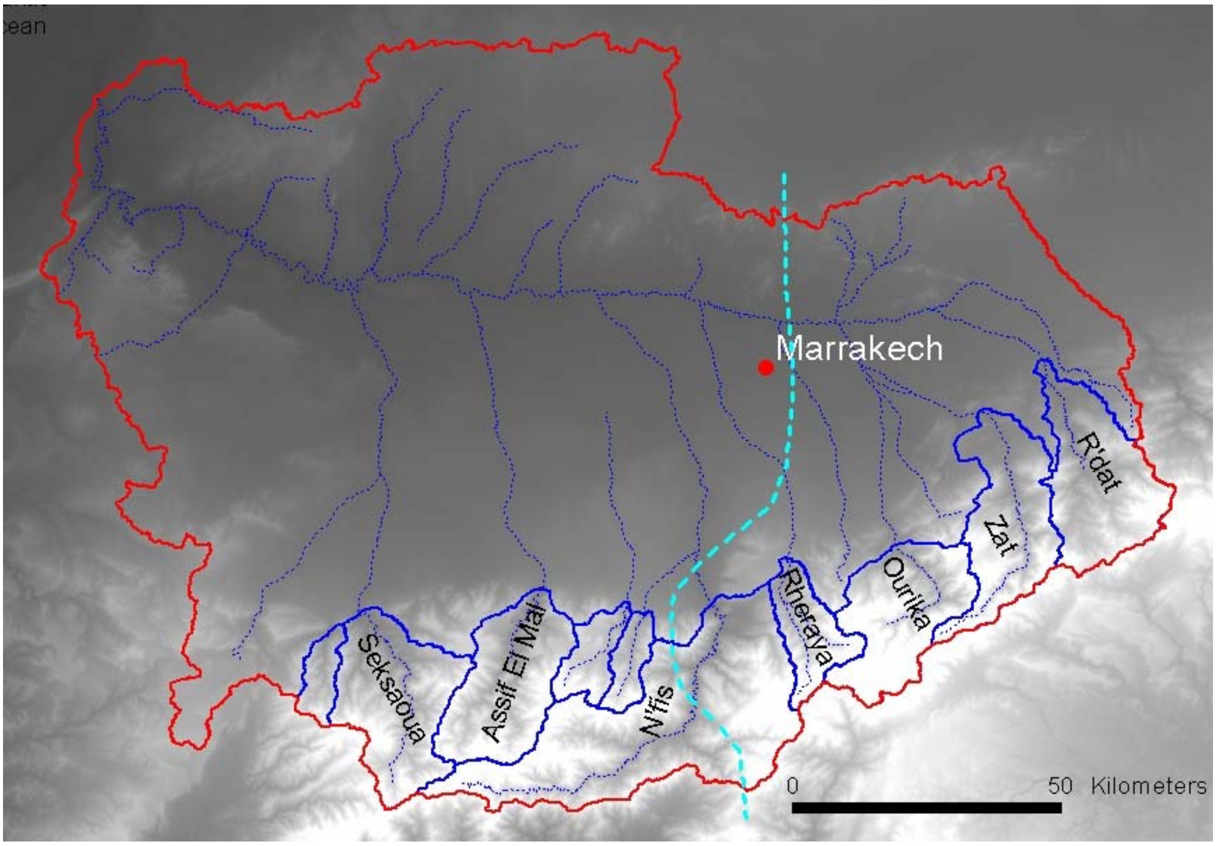

Figure 1: the Tensift basin (red) with the main atlasic catchments; the dotted blue line shows the hypothetical limit between the areas for which oceanic influence is predominant and the areas under a larger continental climate influence

2.2. Geochemical analysis

Measurements of Dissolved Organic Carbon (DOC) and silica content have been used to separate the streamflow contribution of the runoff or shallow (surface) flow from that of groundwater (deep component). DOC levels depend on the interaction between the water and the topsoil, while silica levels depend on the interaction of water with subsurface rock formations. It was found that the slow component (water that spent a long time in the ground) is relatively stable throughout the year and amounts to almost 100% of streamflow in the summer (Chaponnière et al., 2007, Chaponnière, 2005).

2.3. Remote sensing

Time series of low resolution optical images from the SPOT-VEGETATION instrument together with several disaggregation schemes (Chaponnière et al., 2005, Boudhar et al., 2007) based on high resolution images (from LANDSAT-TM and SPOT) have been converted into time-series of Snow Cover Area over the 1998-2005 period. This dataset has been assimilated into our modelling framework in order to:

- Check for missing rainfall events (for ex. the discrepancy between the observed and the simulated snow cover area in Figure 2 translates in an underestimation of streamflow by 27% when observed SCA is assimilated instead of 49% without it);
- Check the relevance of the temperature gradient to separate solid from liquid precipitation;
- Modify the snowmelt intensity through the adjustment of the degree-day factor.

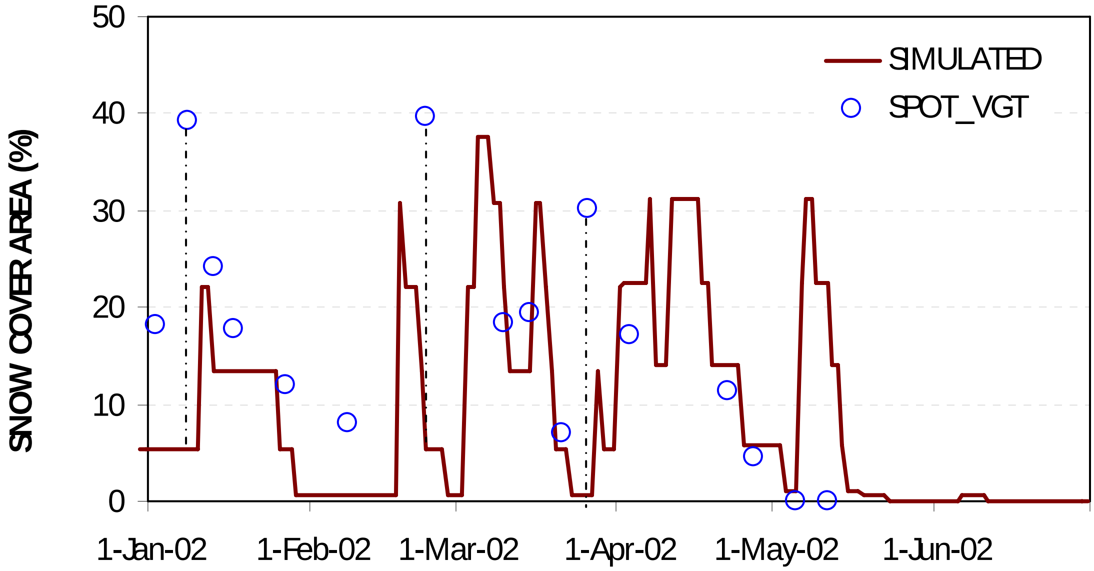

Figure 2: simulated and observed snow cover area; dotted lines show the major discrepancies in the 2002 season (from Boudhar et al., this issue)

3. modelling approach

3.1. Using complex models as "reference" tools: a "top-down" approach:

The purpose of using complex physically-based semi-distributed model is ensure that the interaction between the multiple hydrological processes involved in the area are realistically taken into account. One expects when using this type of model that the transfer processes are governed by physical formalisms which are supposed to be well known, even in absence of measurements to corroborate them. This means that a first guess value of the parameters, as taken from the literature, can be used satisfactorily. It is also expected that dominant processes will be ordered through calibration of the most sensitive parameters; these processes can be classified in three groups: main redistribution processes, second-order exchange fluxes, and anecdotic processes that can be neglected. Finally, it is expected that the physical nature of the formalism is well suited for climate-change scenarios: first, the response of one particular process to a known perturbation is supposed to be mechanistically represented in such models, and, second, the possible modification of the hierarchy of the processes can be naturally modified by climate change. For example, a boom of fast-flood and a considerable reduction in baseflow during summer as a response to higher summer rainfall intensity and lower annual precipitation, or the importance of snow dominated processes if temperature increases significantly in winter, or important land-use changes such as the development of terrace agriculture further up from the valley bottoms..

Two complex models have been used during the SudMed project: the SWAT semi-distributed hydrological model (Arnold et al., 1993) and the ISBA-ES (Boone and Etchevers, 2001) energy balance snow model. The first one is used to understand the relative importance of subsurface runoff, unsaturated lateral diffusion and groundwater outflow, the second one to understand the relative importance of snow drift, snow compaction, sublimation and snowmelt.

There are limitations to the use of such models in absence of process-by-process validation (Chaponnière et al., 2007). Classically, validation of semi-distributed hydrological models is achieved by matching the observed and the simulated streamflow, which has the advantage of integrating lateral redistribution of water across the basin. However, given the complexity of the hydrological cycle in the High Atlas, and the number of interacting processes at several space and time scales, a good performance in simulating streamflow does not guarantee that the intermediate processes are well accounted for: literature-based parameters do not provide a precise enough estimate of most of the processes, and if runoff is often well constrained on a daily basis by streamflow observations, little is know about the relative weight of dryland evaporation, slow subsurface redistribution and groundwater recharge (see Chaponnière et al., 2007 for a comprehensive study of this problem for SWAT and the Rheraya catchment) . There is therefore some compensation between model parameters for these processes when calibrating the model against streamflow observations alone. This phenomenon is well documented as the "equifinality" problem (Beven, 1996). In order to reduce the number of interacting parameters, while keeping a realistic description of the basic features of variability, SWAT has been discretized according to three land surface types (forest, terrace and bare soil) and three soil types. Chaponnière et al. (2007) show that even when one narrows down the range of possible values for each parameter of this crude spatialisation, equifinality is affecting many processes such as transfers and storage in the unsaturated zone as well as evapotranspiration.

Equifinality is also a problem for snowmelt models. In that case, various processes affect the easily measured variables for snow: snow height and snow cover area. For instance, calibrating a complex energy balance model such as ISBA-ES against snow height measurements only won't guarantee that snowmelt is well described. For example, two different models (ISBA-ES and a simpler one) based on different compaction schemes give very different compaction regimes during the winter 2003, which produce similarly acceptable snow height evolution as measured by an ultrasonic sensor; whereas sublimation has been observed (penitents) and simulated in the south of the high atlas (Shultz et al., 2004), no evidence has been found in the northern part. However, a simpler model (Peltier, 2006) simulates some sublimation throughout the snow season with a value close to 0.5 mm/day (Figure 3). Sublimation has the same impact on the disappearance of snow (as monitored for instance by cheap snow height measurements or by remotely sensed snow cover) as snowmelt but does not contribute to streamflow.

Additionnal measurements are therefore necessary to allegedly estimate the second-order redistribution or storage processes. If not, crucial questions with respect to Climate Change scenarios won't be answered: how long does snowmelt need to reach the outlet ? Is it through preferential flow paths ? Additional geochemical analysis (DOC and silica) has already brought some insight into partitioning surface and subsurface flows: it seems that the deep reservoir contribution to streamflow is pretty stable throughout the year. Does that mean that both liquid and solid precipitation contribute to streamflow with a much longer delay than the apparent two to three months between peak snow cover and peak spring baseflow ? We'll see in section 4 how additional observations can help us answer this question.

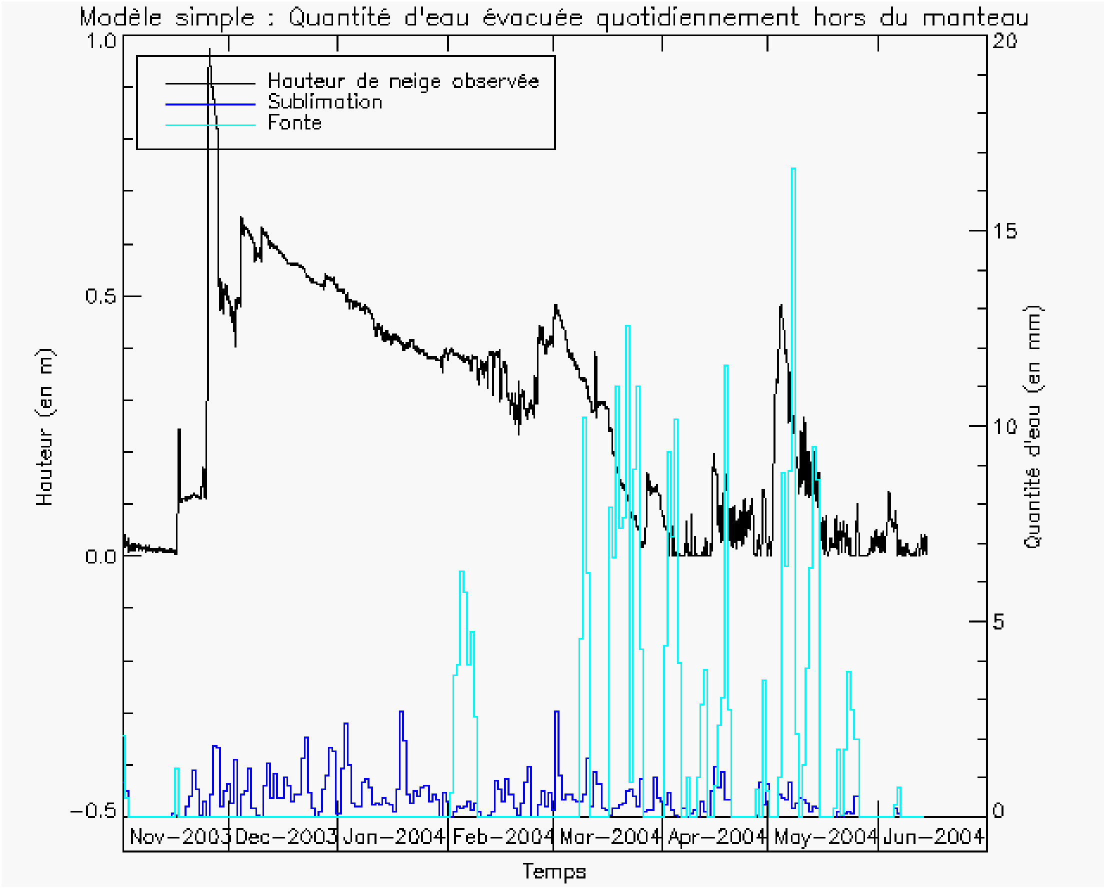

Figure 3: Observed snow height (black line), simulated sublimation (dark blue) and snowmelt (light blue) fluxes (mm/day) at the Oukaimedem station in 2003-2004 (from Peltier, 2006)

3.2. Using simple models for interannual and interbasin variability: a "bottom-up" approach

Given the numerous uncertainties in input and calibration data, and because of the "equifinality" problem, it is tempting to rely on very simple approaches to grasp the main outlines of a particular catchment's hydrological behaviour, and improve model performance by adding missing key processes, such as snowmelt for instance. One can assume that these basic features can be constrained by scarce meteorological station network, while second order processes would need a much more sophisticated and denser observation setup. Two empirical models have been used, SRM (Martinec, 1975) and GR4J (Perrin et al., 2003). SRM uses snow surface as main forcing data, and a classical 1st order autoregressive mathematical model to describe recession. It is semi-distributed in the sense that it computes a water balance for a limited number of altitudinal bands. GR4J is a global conceptual model that uses two reservoirs with different loss functions: a production store and a routing store. Both models are parsimonious in terms of parameters (6 for each model, including 2 for snowmelt). They have been successfully applied to the Rheraya catchment with Nash values close to those of the optimum SWAT simulations. They gave satisfying results fore both low- and high- flows, including extreme cases such as the 1995 storm and the 2001 drought (Boudhar et al, this issue; Simonneaux et al., this issue).
GR4J has been modified in order to simulate snowfall and snowmelt according to the degree-day method. Setting critical temperatures to common values and calibrating only the degree day factor improved greatly the performance of the model.

The interesting point here is that both models perform well during all dry years (esp. 2001, see Boudhar, this issue). We must recall that for an autoregressive model such as SRM, equilibrium baseflow is:

$$Q_{n+1} = aQ_n^{\ b} \Rightarrow \lim_{n \to \infty} Q_n = 1/a^{1/(b-1)} \tag{1}$$

This means that the absolute minimum is non-zero and fixed. Even though mimimum baseflow (Rheraya never dries out contrarily to the N'Fiss catchment) varies from one year to the other, SRM performs fairly well over the last 10 years. On the contrary, in most models based on bucket or multi-bucket representation, such as GR4J, wadi can dry out completely in the summer. For the Rheraya watershed and over the last 16 hydrological years, summer baseflow has been fairly well reproduced by GR4J despite its simplicity. The way those simple models can reasonably describe interannual variability (say for example two dry years in a row followed by a very wet year) with the current parameter values should be studied with greater attention. It is indeed an important issue in hydrological forecasting in the context of climate change. One can expect that even if these models are robust, the simplicity of the description is perhaps too limiting for climate change scenarios. However, the relatively good performance of both models over the last decade despite its large interannual variability is in favour of using them for that purpose.

4. Future work

In this section we want to show how several additional measurement campaigns or other data-sources could help us constrain further our modelling approach, and describe the strategy to investigate climate change impact on the hydrological regime of the High Atlas.

4.1. Enhanced observation system

- enhanced monitoring of water volumes extracted by seguias along the river:

Most of the water extracted for irrigation purpose is taken in the piedmont area below the selected outlets of our catchments (chosen as the streamflow gauge station), and thus don't interfere in the catchment modelling. Anyway, many seguias inside the catchment have been up to now only crudely accounted for in our distributed modelling system. The annual pattern and the localization of the diverted flows is important to assess the dynamics of low-flows. A quick measurement campaign achieved in july 2007 has shown that the amount of water diverted by these internal seguias was of the same order as the flow at the outlet at this time (0.8 m3/s). This value shows their importance in the hydrologic behaviour of the catchment.

- enhanced geochemical analysis: a useful tool to provide with water origin and transfer timescales;

Isotope studies could bring us more insight on two important aspects:
1- the relationship between the origin of streamflow or groundwater recharge and altitude (Raibi et al., 2006), as well as the characteristic timescale of transfer from precipitation to groundwater.
2- the composition of streamflow water with respect with its origin as solid and liquid precipitation and the importance of sublimation. As stated earlier, this is fairly important to determinate whether the slow redistribution processes have a seasonal, an annual, or even a longer characteristic time scale.

- additional remote-sensing data: Thermal-Infra-Red (TIR) data for spatialisation and melting monitoring;

TIR remote sensing is not yet extensively used to help with spatializing the atmospheric forcing (air temperature mostly) in these mountainous regions characterized by very sparse meteorological station networks; although the current resolution of the sensors onboard satellites with a daily revisit period (such as MODIS) is too low to ensure good representativity of local air temperature compared to large pixels, it could be improved by high resolution TIR satellite missions such as the MISTIGRI proposal (CNES). On the basis of low resolution data only, given the lack of measurement of air temperature at high altitude, it could be a “better than nothing” solution.

- micrometeorological methods: providing a comprehensive real evapotranspiration;

Evaporation is not well known; terrace agriculture is a significant contribution to basin-scale evaporation and can me monitored with high-resolution images such as that provided by FORMOSAT (Duchemin et al., 2008), but the reduced evaporation from the rocky bare soils highest parts of the catchments can be difficult to assess; it could be useful to set up micrometeorological stations (eddycorrelation, and microlysimeter for snowmelt in altitude) as well as scintillometer transects to try to reduce the uncertainty on evaporation and sublimation estimates at the catchment scale.

4.2. Climate change scenario

There is a clear decreasing trend in annual precipitation at the Marrakech synoptic station over the last century. For the Rheraya catchment, the long-term averages over 1925-1970 of annual runoff, annual precipitation, and the ratio between both fluxes are all higher than the corresponding averages over the period 1971-2002 (Chaponnière, 2005). It’s therefore probable that the magnitude or the relative importance of some of the transfer processes or the losses (evaporation for instance) have changed from one period to the other. Even if one trusts the longterm calibration of the simple models above, predicting the impact of Climate Change on the hydrological regime of the High Atlas is a difficult task. What can be done is to use MeteoFrance and ECMWF climate scenarios together with a thoughtful desegregation scheme of the climate forcing (these datasets are often elaborated at very low resolution, of the order of several thousands of square kilometers). Given i- the equilibrium between the advantages and the drawbacks of both modelling strategies (“top down” and “bottom up” approaches), and ii- their comparable performance in simulating streamflow during calibration/validation split-sample studies, it is not yet clear which approach will be used preferentially to generate this response. The very simple models have the considerable advantage to be computationally very efficient and therefore particularily adapted to Ensemble Prediction simulations (Shaake et al., 2006). This feature could lead to design a first version of an Uncertainty Simulator on the basis of the simple models and test it on selected Climate Change scenarios.

5. conclusion

The SudMed project is a typical study of the “Prediction in Ungauged Basin” initiative (Sivapalan et al., 2003). Its results can be used to provide water authorities with sensible answers on the way the hydrological regime of the headwater catchments could respond to Climate Change. By mean of various modelling strategies, involving simple as well as complex modelling toolboxes, combined with additional short-term measurement protocols and (as much as possible) easily available ancillary information such as Remote Sensing data, the project has built an original approach that will be amplified in the next few years.

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