Modelling runoff in the Rheraya Catchment (High Atlas, Morocco) using the simple daily model GR4J. Trends over the last decades.

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Keywords: GR4J, Runoff, Modelling, Watershed budget, Drought, Snow

Introduction

The Tensift watershed (20500 km2), located around Marrakech (Morocco) is experiencing water resource shortage resulting from the strong increase of water consumption due to both urban and agricultural development, and more and more frequent drought periods which may prefigure the ongoing climatic changes. Water management in this area would benefit from tools based on a reliable knowledge and modelling of the water fluxes. The SudMed project is aimed at a better understanding of the local hydrological cycle, through collaboration with the local watershed agency (Chehbouni et al., 2008). Considering that the High Atlas Range (maximum altitude 4167 m) is from far the major water source of the Tensift watershed, the hydrological modelling of these mountains is necessary to quantify the inputs to the Tensift system and run scenarios for the future.

The approach of the SudMed project is combining complex distributed semi-physical hydrological modelling and more simple empirical ones (Boulet et al., this issue). This joint effort is aimed at studying the physical processes involved in the redistribution of water through the catchment. The lack of data in this area is critical and therefore this study belongs to "ungauged basins" initiative. Compared to physical or semi-physical distributed models like SWAT (Arnold et al., 1993), conceptual models like GR4J (Perrin, 2003) offers a good alternative when detailed physical parameters are lacking to run such models.

The present study is aimed at the hydrological modelling and budget assessment of one of the main catchments of the High Atlas range, the Rheraya (224 km^2) whose altitudes are ranging from 1084 to 4167 m (fig.1). The hillslopes are covered by degraded rangelands with little vegetation and a stone cover usually over 50%, whereas a thin strip of irrigated crops are found in the valley on either side of the river. The precipitations are very variable in time, with an average of about 350 mm/year at the outlet (Tahanaout). At the watershed scale an average value of 490 mm was estimated in this study, approximately one third of it falling as snow. The evapotranspiration in this area is very little known, but a weather station installed by the SudMed project at Aremd (1900 m) gave an average value of 1073 mm for ET0 from 2003 to 2006. The average streamflow at Tahanaout over the period study (1989-2006) is 1.44 m^3/s (202 mm). The distribution of streamflow throughout the year is given in figure 2.

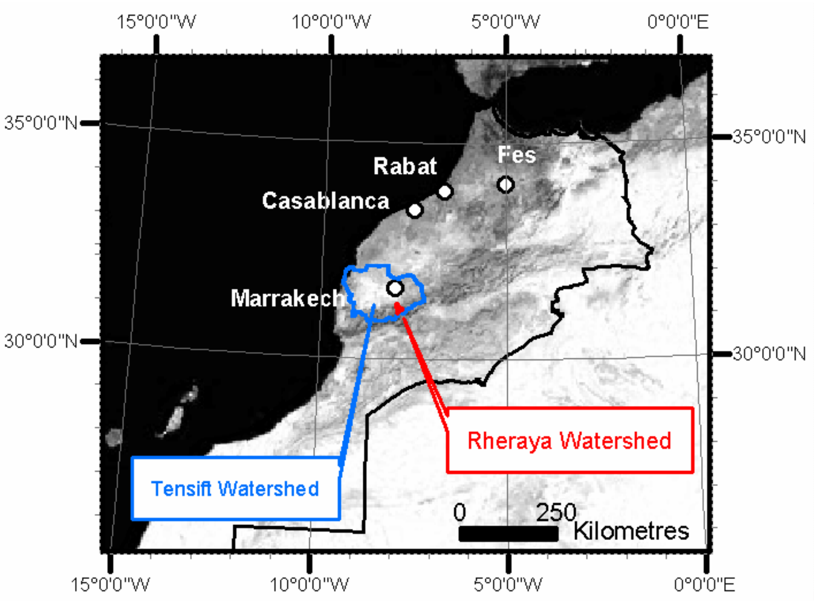

Fig.1 – Location of the Study area

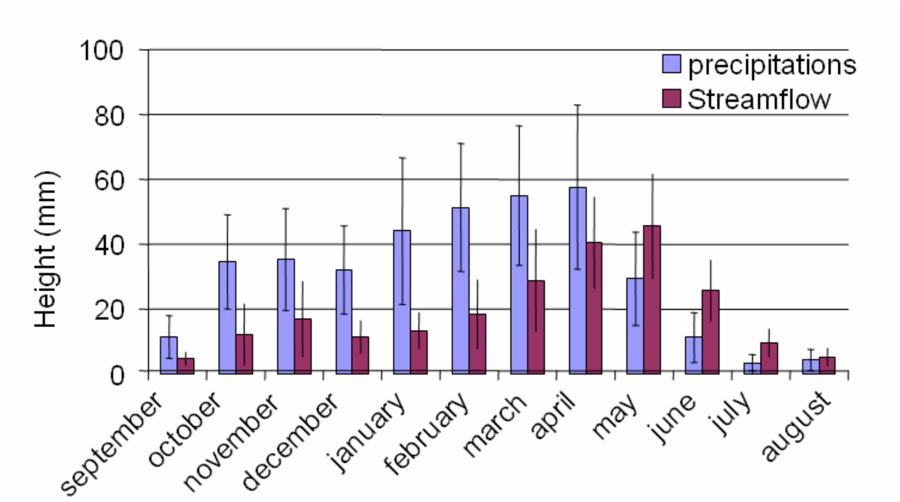

Fig.2 – Monthly distribution of streamflow and rainfall at Tahanaout over 1970 – 2002 (from Chaponnière , 2007)

Materials and Methods

The GR4J Model

GR4J is a well known and widely tested conceptual model based on only four parameters (Perrin et al., 2003). It was built through a bottom-up approach by step-by-step increase of the complexity of simpler models, the previous version being GR3J (Edijano et al., 1999). In short, this model takes into account daily rain and evapotranspiration that first go into a production store — whose volume is parameter X1 — or generate direct runoff in case of high intensity (fig.3). Percolation from this first store meets the eventual direct runoff and 90% of it is directed in a deeper routing store — whose volume is parameter X3 — the 10% remaining generating river runoff directed to outlet though unit hydrogram whose delay is driven by the X4 parameter. The deep store also percolates and generates delayed runoff.

Both the routing store and the river runoff are prone to deep infiltration outside the system through an exchange parameter X2. This “lost” water flows either to neighbouring catchments through karstic network (which is no the case here), or feeds the downstream aquifer directly without transiting by the outlet, which is an important process here in the Haouz plain (JICA, 2007).

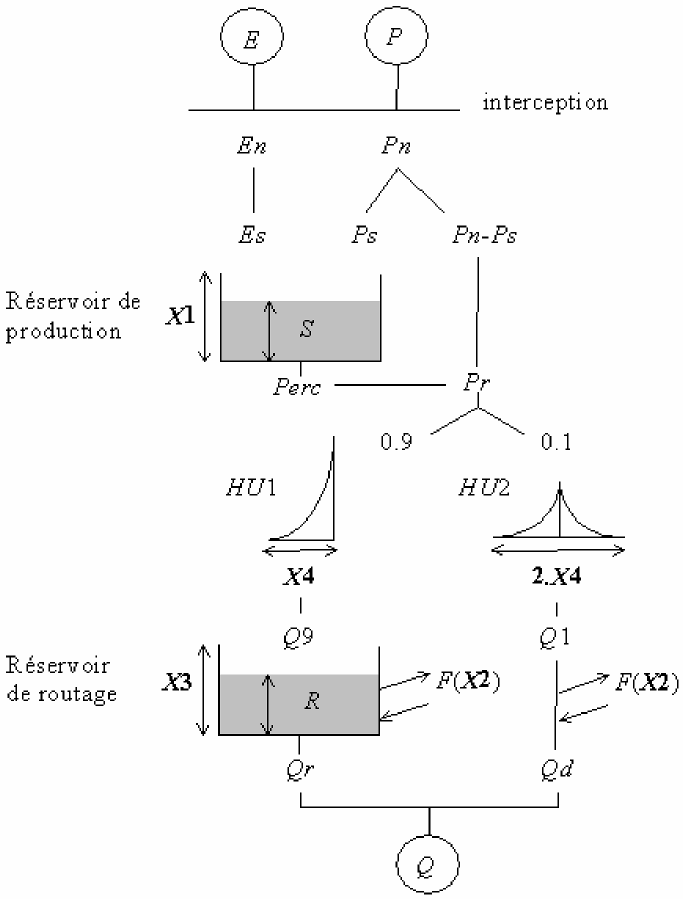

Fig.3 – The concept of the GR4J model (from Perrin, 2003)

The initial GR4J model doesn’t account for the snow contribution to the pattern of streamflow. Makhlouf proposed an additional module to solve this problem (1994). This module relay on a stratification of the watershed in some altitude bands in which the snow is melted using de degree day model. The module assumes that the user provide each band with daily snowfall values. Here we propose a simple temperature based snow generator, that uses temperatures observed at a weather station and calculated for each band though a standard altitudinal gradient. The Makhlouf model considers a complex snow melting process involving a proportion of rain in the snow. As a result it was driven by five parameters, a snow majoration factor X’1, a rain fraction in the snow X’2, a rain melting coefficient X’3 and a temperature melting coefficient X’4. An additional fixed parameter was also the temperature threshold TT for the melting process (0°C).

These five parameters were sometimes difficult to figure out physically and their number may induce equifinality problems as it is not possible to control all the intermediate variables that are generated. We simplified this model in removing processes modifying snow after generation (snow increasing X’1 and partial conversion to rain X’2), which are redundant with the snow generation processes. We kept only as adjustable parameter the degree day coefficient X’4 for temperature melting, and the parameter driving snow melting due to rain X’3. Conversely, the threshold temperature above which snow melts TT, which was fixed in the initial version, was considered as an adjustable parameter.

Climatic data

We used rainfall data recorded at the Tahanaout outlet from 1975, and rainfall, snow high and temperature data recorded at Oukaimeden (2650 m) from 1989 by the staff of the CAF hut.

The figure 4 shows two distinct periods in the temperature series at Oukaimeden, 1990-1997 and 1998-2007. Between these periods the temperature raised from about 0.8 degree as detailed in table 1. At first glance this sudden rise may let think to an instrumental bias, but this tendency was confirmed by recordings at Lalla Takerkoust in the Haouz plain just downstream the Rheraya watershed. The Oukaimeden recordings show a decrease in the proportion of snow in the precipitation, snow was merely higher than rain until 1997, and becomes lower from 1998. This tendancy can be linked to the raise of temperatures from about 1998. Both in Oukaimeden and in Tahanaout (fig. 5) the precipitations show no clear trend.

GR4J requires daily values of actual evapotranspiration (ETR). The reference evapotranspiration ET0 was accounted for using the Hartgreaves formula based only on daily temperature and extraterrestrial radiation. ETR of the soil surface is usually lower than ET0, especially in mountain areas where the vegetation is scarce and the soil covered with stones. Thus, the ET0 value was reduced by an arbitrary adjustable factor to account for the actual surface properties.

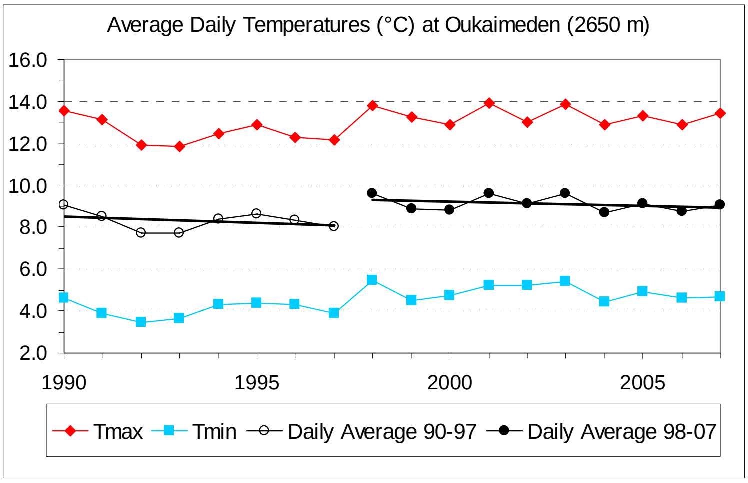

Fig.4 – Temperatures recorded at Oukaimeden. X axis shows the hydrological years (1990 : 1/09/1989 – 31/08/1990).

	Average of daily values		
	Tmin	Daily average	Tmax
1989-1996	4.1	8.3	12.5
1996-2007	4.9	9.1	13.3

Tab.1 – Temperatures at Oukaimeden (2650 m) since 1989.

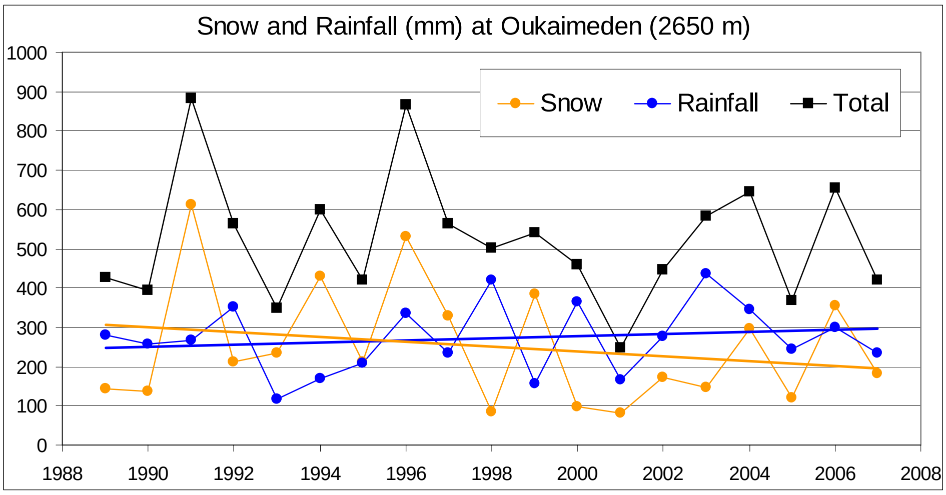

Fig.5 – Time series of Precipitation, rain and snow at Oukaimeden from 1989 to now.

Stream flow data

The analysis of historical data shows a clear and dramatic decreasing trend in the stream flow at Tahanaout since 1925 (tab. 2).

	1925-1970	1970-1997	1997-2006
P (mm)	440	380	336
Q (mm) *m3/s*	360 *2.56*	223 *1.6*	105 *0.75*
Q/P ratio	0.82	0.59	0.31

Tab.2 – Rainfall (P) and Streamflow(Q) of the Rheraya from 1925 to now.

The 1970 drop is clearly linked with the decrease of precipitations which affected many areas in north Africa and especially in morocco. This decrease of precipitations is also visible in Marrakech (Chaponnière, 2005a), and in other locations inside Morocco (RDH50, 2008) but seems not to have affected the coastal areas (RDH50, 2008). This trend was also observed for some places west of Algeria (Hirche, 2007). Moreover, the flow decrease is much steeper than the rainfall decrease, which can be easily explained by the fact that, especially in arid areas, the evaporation part is important and don't reduce proportionally to the rainfall, affecting the rainfall / flow ratio.

Focusing on recent data available at Tahanaout, the trend is clearly visible (fig. 6). The two periods mentioned before can be related with the above mentioned changes in temperature and snowfall at oukaimeden, and to a minor extent to changes in rainfall. This shows a significant change in the Rheraya hydroclimatic regime between 1997 and now, although it is not possible to conclude now to a long term trend.

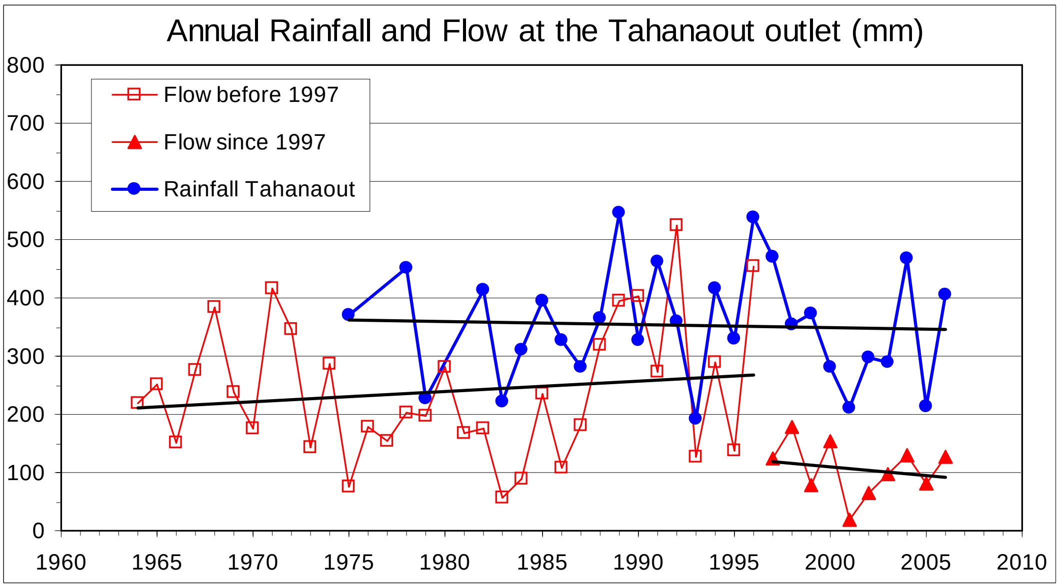

Fig.6 – Rainfall ad Streamflows recorded at Tahanaout (1084 m)

Streamflow at Tahanaout are measured in a unstable rocky bed based on a scale. The bed is changing from time to time as strong events occur. Thus, despite the monthly gauging frequency, rating curves are difficult to compute and may soon loose their validity. In this context it is quite normal that the daily flow values obtained from the water agency (ABHT) suffer from some mistakes. Because it was practically impossible to reprocess 20 years of scale measurements, we used a quick empirical correction method. The daily flow values were compared with the gauging values available, selecting only the ones corresponding to stable days, i.e. excluding the gauging corresponding to flood days, for which an instantaneous flow measure can't be compared with a daily average. Strong discrepancies appear sometimes between gauged and daily flow value, and often over periods covering several gaugings, which reinforce the hypothesis of the use of a wrong rating curve. A correction factor is computed for each selected gauging, which is the ratio between the gauged and the daily value. To extent the computation of a factor for each day between two gaugings, we assume a linear variation of this correction factor between two successive gaugings. The implementation of this empirical correction improved greatly the NASH coefficient during the first trials of calibration of GR4J.

Results

Model calibration

Some compensations may occur between model parameters when calibrating the model against streamflow observations alone, according to the well known equifinality problem (Bewen, 1996). This problem may limit the physical soundness of the model, and limit the accuracy of scenario testing beyond the calibration conditions. Despite its simplicity, GR4J is also prone to compensation problems and may give good NASH efficiency in the estimated vs observed flow intercomparison, even with wrong data input or wrong values for internal variables. For instance, the range of values of the X2 parameter is large enough to allow X2 to compensate for any bias in the ETR, rainfall or Flow variables.

The model calibration was achieved through the following steps :

1- Precipitation calibration

Spatialisation of precipitations in a mountainous watershed, moreover in arid areas, is a real challenge, especially since only two stations are available for 224 Km^2. In this context our objective is not to recover the actual precipitations but to get realistic daily time series at the catchment's scale. The precipitation values from Oukaimeden were obtained by adding direct rainfall and snow water equivalent assuming a snow water height conversion coefficient of 0.1, estimated from measurements done during the 2007-2008 season at Oukaimeden. These total precipitations were averaged daily with the Tahanaout values, generating a virtual station at the averaged altitude of 1850 m, from which a gradient was applied to generate the precipitations for any altitude.

The distribution of the precipitations was validated using the values observed at Tahanaout and Oukaimeden, and with the maximum possible values commonly admitted at higher altitudes (about 800 mm). In order to fit this curve we made use of two adjustable parameters: the altitude of the virtual station, and the gradient. Because the two stations used are not obviously representative of their altitude slice in the whole basin, we allow for a modification of this reference altitude. The final altitude was chosen to 2300 m instead of the theoretical 1850 m value, which indicates that the virtual station was overestimating precipitations. This is not surprising as Oukaimeden is located on mountains well exposed to the atmospheric circulation and receive a lot of precipitations. Besides, this is one reason why it was chosen to settle the Marrakech ski resort some decades ago. The gradient was fixed to 0.002 mm/m, which is close to the value of 0.0024 obtained by Chaponnière (2005a). The resulting precipitation distribution is presented in figure 7.

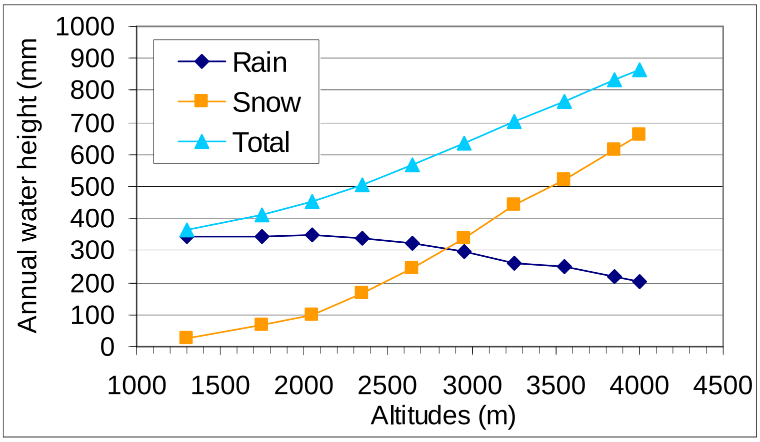

Fig.7 – Distribution of rainfall and Snow altitude as modeled for input in the GR4J model

2- Snow / Rain balance calibration.

From the distribution of precipitation determined in the previous step, the snow generation was achieved using a simple temperature threshold using the maximum temperature of the day. To estimate temperatures at all altitudes, the same method as for precipitations was used, based on a reference altitude and a gradient. These two parameters were initially set using the actual altitude of Oukaimeden (2650 m), and the temperature gradient of 0.007°C/m obtained by Chaponnière (2005a). The threshold applied to the maximum daily temperature for snow appearance was chosen to be 9°C, in order to force the snow generated to agree with the average snow observed at Oukaimeden. For other altitudes, we could only check that it was in agreement with common observations, i.e. no significant snow below 1500 m (figure 7). At the end of the GR4J calibration process, we came back to the calibration of these three parameters to optimize them, and they appear to be rather stable as the values fitted were close to the first ones (2730 m altitude, 0.006°C/m gradient, 7 degrees for Tmax snow threshold).

Taking into account the areas of the various altitude slices considered, the overall contribution of snow in the Rheraya is estimated to 34% of the total of precipitations (167 mm and 494 mm, respectively, for 1989-2006).

3- Snowmelt calibration

The snowmelt driven by rain for day i, SMR(i), is obtained by simply multiplying the rainfall of day I, R(i), by the X'3 coefficient :

$$SMR(i) = R(i) * X'3$$

The snowmelt due to temperature for day i, SMT(i), rely on the temperature threshold and the melting coefficient through a simple degree day equation as follows:

$$SMT(i) = X'4 * (Tm(i) - TT)$$

These factors were first adjusted manually on the basis of two intermediate physical variables, the snow pack and the snow melting pattern for each altitudinal band. In fact the snow pack alone is not a reliable criteria as some configurations were found with good snowpack dynamic, but poor snowmelt dynamic, which was occurring almost all along the season. In order to obtain a reasonable melting pattern with the melting occurring mainly at the end of the snow season, we had to delay the melting process by increasing the maximum temperature threshold, and on the other hand by increase the melting intensity so that no snow remain after June. At the end of the GR4J calibration process, we also re-calibrated these three parameters, (after recalibrating the snow generation ones of step 2). The final values were 9.2°C for the temperature threshold, 27.9 mm.°C^{-1} for the degree days snowmelt factor, and 5 mm.°C^{-1} for the rain melt parameter. These two later values mean a very quick melt which has no physical meaning, but on the whole they give satisfactory snowpack and snowmelt dynamics, along with improved Nash criteria. Linked to this partially unrealistic behaviour, it should be noticed that the snowmelt occurs here through two processes. The first is the rain melting occurring for temperatures high enough to generate rain but too low to generate "degree days" melt. This process occurs many times during the season but generates little melt each time. The second process is the degree days melt occurring when the max temperature is above the TT threshold, and occurs jointly with rain melt when rains occur. This second process is unrealistically quick but give an overall satisfying snow dynamic throughout the year. Thus the melt process is still a bit complex in the actual configuration, and probably not well balanced between rain and temperature melt. Further simplification should be considered for example by removing the rain melt process and focusing on temperature processes. At this stage, we use it "as is" and only validate the results as satisfying the snowmelt dynamics.

4- GR4J calibration

After validation of the previous steps regarding precipitations and snow inputs, we calibrated the GRJ4 model itself, adjusting parameters X1 to X4. Considering here the limited representativity of rainfall data especially during strong events which are mostly locals, and the expected poor quality of flow measurements, we chose to optimize the square root of flows (Nash(VQ) instead of flows themselves (Nash(Q)). This choice means that lesser weight will be put on higher flows, as we assume that these flows are affected by larger errors. Moreover, through this choice we focus more on the global trend of the flow, and less on short and strong events, which involve processes at the hour scale whereas GR4J is designed for daily scale modelling.

After pre-processing of the input data, the dataset available ranges from 1 September 1989 to 31 August 2006. The first year (1 September 1989 to 31 August 1990) was removed from the calculation of the Nash to account for the initialization period of the 2 water stores. The ultimate Nash(VQ) computed obtained was 0.568 which is low compared with well gauged basins but is rather satisfactory in our context (fig.8). As a basis for comparison, in other watersheds of the high Atlas (Ourika, Zat, Rdat, N'Fis), using basic versions of GR4J, the Nash(VQ) values were around 0.45 and 0.55 for periods ranging from 16 to 30 years. It is quite clear that these seemingly poor results were largely due to the low quality of rainfall / flow time series.

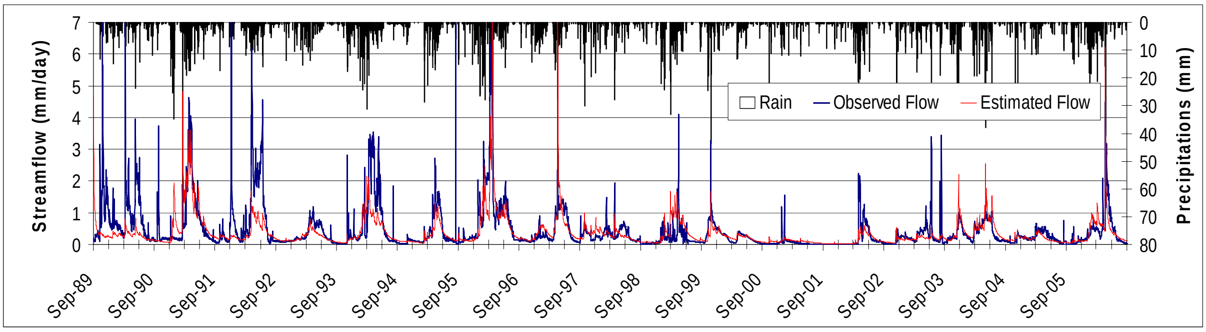

Fig.8 – Hydrogram of the Rheraya. Comparison of observed to simulated values

Nevertheless, after calibrating GR4J over the 17 years available, the Nash(Q) computed only on the 90/91 hydrological year — considered by previous studies as one of the best regarding data quality (Chaponnière, 2007) — gave a Nash(Q) of 0.72 which is encouraging when compared with the Nash(Q) = 0.83 found by calibrating the SWAT model over this single year. This encouraging result shows that GR4J calibration over long periods seems to manage a good trade-off between errors and to reach in this way a good tuning of the model. Moreover, if GR4J calibration was achieved on this year only, GR4J works as good as SWAT with a Nash(Q) of 0.85.

GR4J was also able to simulate correctly the low water level observed for the last years due to drought periods, and more generally the strong interannual variations of streamflow. Thus, despite it's very low flow, it appears that the 2001 year is very well modeled whereas it was considered by Chaponnière (2005a) as doubtful.

Catchment's fluxes balance.

In order to validate the GR4J calibration, and especially its physical soundness, we look at the balance of the fluxes in and out the watershed. This balance is defined by:

Precipitations (P) = Streamflow (Q) + Deep percolation (DP) + Evapotranspiration (ETR)

The budget obtained for the Rheraya is presented in tab.3.

In our context like in many others, P and Q are the best known variables. But DP and ETR usually suffer from high uncertainty and may compensate a lot in any model if one doesn't pay enough attention to the validation of these variables.

The DP for the Atlas range was estimated by the local watershed agency to be approximately half the surface flows. Our values show a higher proportion of DP, which is not very probable. The fact that the Q modeled by GR4J produces only 85 % of the actual flow (133 instead of 171) may explain part of this discrepancy, but is not enough, and this fact points the limits of GR4J regarding these physical processes.

The ETR factor was adjusted to fit the watershed budget to a reasonable balance, e.g. forcing deep percolation to get out of the watershed. After various trials on several watersheds, it was found that a value of ETR around 0.25*ET0 gave a reasonable catchment balance, although it was impossible to fully constrain this balance. The resulting ETR was 238 mm for the Rheraya, which is in good agreement with the previous SWAT experiments (Chaponnière, 2005a) which mention and average value of 220-250 mm/year for cumulated ET (i.e. 0.6 – 0.7 mm/day). This ETR value is half the total precipitations on the area, which seems a realistic value for these environmental conditions.

It would be very useful to measure ETR on the mountain rangelands covering most of the hillslopes, using for example the eddy correlation method or scintillometers. This information would allow to solve the ambiguity with deep infiltration fluxes. These fluxes contribute to a major extent to the Haouz aquifer recharge, which is one poorly known variable hampering the accurate modelling of this aquifer.

Precipitations *(mm/year)*	Stream flow *(mm/year)*	Deep percolation *(mm/year)*	Evapotranspiration *(mm/year)*
501	133 (actual 171)	132	236

Tab.3 - Budget of the Rheraya catchment resulting from GR4J. Average yearly values between 1989 and 2006.

Snow distribution

We showed previously that the amount of snowfall had slightly decrease at Oukaimeden since 1989, correlated with the temperature rise. The simulations of the snowpack also show a sensible decrease especially around 1997 (fig.9). At some altitude (3250 m), this decrease is much more pronounced than the overall decrease of snowfall. This observation is consistent with the fact that the temperature has a double effect on the snow dynamic, reducing snowfall and then accelerating the melt. This simple modelling shows also how this effect may be very marked at some altitudes, which are close to the climatic boundary conditions for snow accumulation. The decrease of the snow pack modeled here is moreover well correlated with human testimonies, in that either mountain people or even skiers all acknowledge this fact. Boudhar et al. (2007) studied the snow surfaces dynamics using SPOT-VEGETATION images since 1998. It would be interesting to gather older images (NOAA AVHRR) to go back further in time to validate the change showed in this study.

The relative contribution of snow to the hydrogram was tested by simply removing the snow formation from the model and keeping the initial calibration. The Nash(VQ) coefficient drop from 0.568 to 0.426, emphasizing the snow’s importance in the hydrological processes. The comparison of the two hydrograms shows also that the snow reduces the flow and it’s strong variations during winter (December-March), and conversely contributes to a large part to the base flow not only in spring but also in summer (fig.10). This contribution appears also to be very variable from one year to another depending on the snow amount, between about +50% and +25% in spring, and between about +25% and +5% in summer. The high variability and sensitivity of this snow component is here also a striking figure of this catchment.

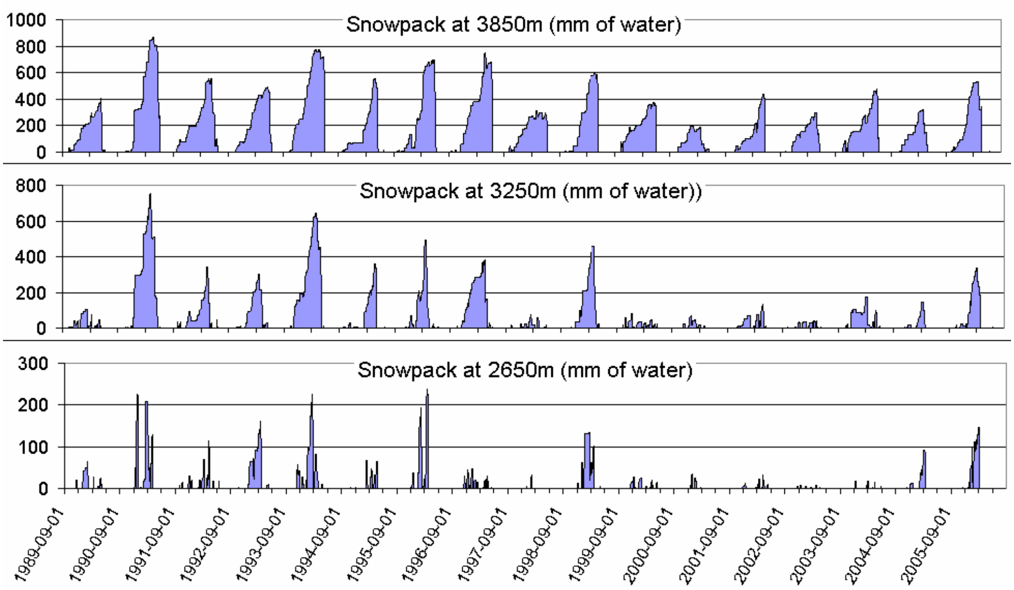

Fig.9 – Distribution of the modeled snowpack at various altitudes

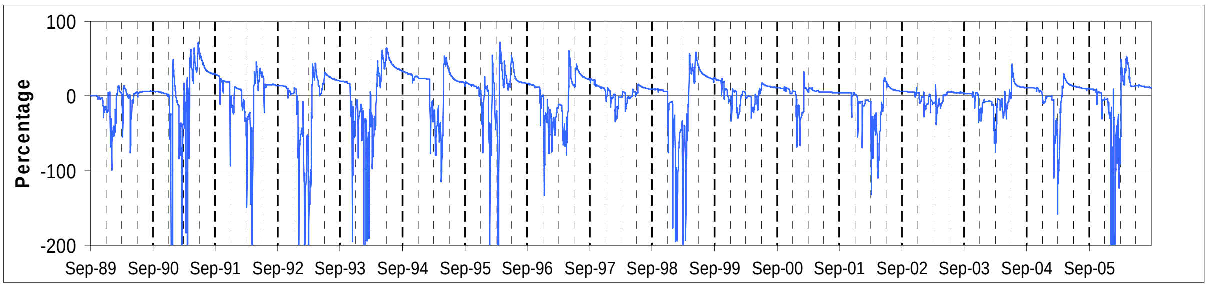

Fig.10 – Time distribution of the relative difference (Nominal streamflow - Streamflow witout snow) / Nominal streamflow. The positive values show the positive contribution of snow to streamflow.

If a calibration is achieved without snow, the Nash rises to 0.506, which remains significantly lower than without he snow module (0.568).

Evidence of two functioning periods

The ratio between streamflow computed by GR4J and observed stream flow is significantly different for the two periods highlighted, i.e. before and after 1997, with the values of 68% and 109% respectively. Moreover, if the calibration is applied on the 89-96 period only, then theses ratio are respectively 84 % and 137%, which represent a shift of 39% in the second period relatively to the first one. This means that actual stream flows are much lower than the computed ones in the recent decade. This difference may be due to a change in the basin hydrological processes — linked to the changes already highlighted affecting all hydroclimatic variables — that would not be accounted for by GR4J due to its relative physical weakness.

Nevertheless, an other hypothesis worth raising is the increased water use by agriculture, triggering an increased evapotranspiration. Indeed, a strong development of tree cultivation has occurred in this basin since 1990. For example, the Imlil area, which was occupied by wheat in 1990, is nowadays completely covered with apple-trees. The trees have a longer vegetation period (leaving their leaves only 3 months between December and march, and a stronger water consumption. Moreover they often include understorey of annuals.

To corroborate the hypothesis of stronger evaporation, we added an arbitrary term of 0.25 mm to the daily ETR from 1996 to 2006. This crude modification improved the water budget as shows in table 4. The Nash(VQ) increased to 0.58 after recalibration, and moreover produced a balance of fluxes in the basin corresponding more to the expected one, with deep percolation decreasing to 66% of the runoff.

Precipitations *(mm/year)*	Stream flow *(mm/year)*	Deep percolation *(mm/year)*	Evapotranspiration *(mm/year)*
501	139 (actual 171)	92	270

Tab.4 - Budget of the Rheraya catchment between 1989 and 2006, with ETR increased of 0.25 after 1996.

Thus agricultural takings seem to have a great importance on the basin functioning. Anyway in most case they can be neglected as assumed by Chaponnière (2005a), as long as there are taken into account in the global evapotranspiration of the basin. Only strong modifications of this water extraction occurring during the modelling period and not taken into account may affect the model efficiency, which may be the case here. 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 m^3/s). This value shows their importance in the hydrologic behaviour of the catchment.

Conclusion

Compared with the initial GR4J version and its associated Makhlouf snow module, we achieved a better segmentation of the precipitation processing allowing a better control of this input. We also added to the GR4J “spreadsheet” the computation of the watershed budget to control the physical meaning of the calibrations.

In spite of its simplicity, the use of GR4J in the Rheraya catchment gives interesting insights about its functioning. We emphasize the changes that have occurred since the year 1997. It should be noticed that these changes follow a previous change observed around the year 1970, but it is too early at this stage to conclude to a definite climate change. The snow dynamics appears to be very sensitive and to greatly amplify the climatic variations observed. The decrease of the streamflow appears to be much more rapid than the decrease in precipitations, which let us imagine how dramatic could be the consequences of any other level of climatic change with reduced precipitations and/or increase of temperature. Anyway the exact intensity of the threat needs further studies to be exactly assessed, and especially the balance between deep percolation and evaporation has to be better estimated to see what has and will happen to these important fractions. Indeed deep percolation is not a loss but a very valuable source for the Haouz aquifer.

This model seems therefore well adapted to poor quality data assuming long enough time series are available, and it is able to depict correctly very different hydrological years, which could make it a candidate tool for simple climate change scenario testing. It is true that the lack of physical soundness may hamper the use of such models for scenario testing. Nevertheless, the very contrasted years tested since almost 20 years in the Rheraya looks like a test of climate change scenario, which was successfully managed by GR4J. The relevance of scenario's extrapolation is also questionable for physical models, as it is difficult to be sure to depict exactly the physical processes occurring in the real world. Physical models may suffer from equifinality problems unless they were fully validated for all processes, which is a huge task requiring large amounts of data.

Acknowledgements

We are grateful to IRD for funding the SudMed project and the CREMAS team, as well as the french Ministère des Affaires Étrangères and the Moroccan Ministère de l'Éducation Nationale, de l'Enseignement supérieur, de la Recherche Scientifique et de la Formation des Cadres for funding the Programme d'Action Intégrée Volubilis « Gestion durable des ressources en eau dans le bassin-versant de Tensift (région de Marrakech) » n° MA/148/06). We also thank the ABHT (Agence de Bassin Hydraulique du Tensit) for providing us with data. Finally a special thank is addressed to late Jean Minet and his wife Michelle, the managers of the CAF (Club Alpin Français) hut in Oukaimeden for their invaluable help in giving us the climatic data they have been collecting daily since almost 20 years, and without which this study wouldn't have been possible.

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