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Estimation of antecedent wetness conditions for flood modelling in Northern Morocco

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Abstract

In Northern Morocco are located most of the dams and reservoirs of the country, while this region is affected by severe rainfall events causing floods. To improve the management of the water regulation structures, there is a need to develop rainfall-runoff models to both maximize the storage capacity and reduce the risks caused by floods. In this study, a model is developed to reproduce the flood events for a 655 km^2 catchment located upstream of the 6th largest dam of the Morocco. Constrained by data availability, a standard event-based model was developed for hourly discharge using 16 flood events that occurred between 1984 and 2008. The model was found satisfactory to reproduce the runoff and the temporal evolution of floods, even with limited rainfall data. Several antecedent wetness conditions estimators for the catchment were compared with the initial condition of the model. These estimators include the discharge of the previous days, the antecedent precipitation index and a continuous daily soil moisture accounting model (SMA). The SMA model performed the best to estimate the initial conditions of the model, with $R^2 = 0.9$. Its daily output has been compared with ASCAT and AMSR-E remote sensing data products, both were able to reproduce with accuracy the daily soil moisture dynamics at the catchment scale. This same approach could be implemented in other catchments of this region for operational purposes. The results of this study indicate the potential usefulness of remote sensing data to estimate the soil moisture conditions in the case of ungauged catchments in Northern Africa.

1 Introduction

Northern Morocco is the rainiest part of the country, with a Mediterranean type of climate influenced by the nearby Atlantic Ocean. This region hosts some of the largest dams and reservoirs of the country (Bouaicha and Benabdelfadel, 2010), which are mainly used for water supply and irrigation. Like other regions bordering the Mediterranean Sea the region is also affected by violent flooding events (Llasat et al., 2010).

Torrential rainfall is the main driver of flooding in Northern Morocco, causing extended damages to populations and infrastructure (Bouaicha and Benabdelfadel, 2010). Estimates of flood volumes are needed to improve dam management in this region which focuses on maximizing the storage of the reservoirs to address regional water scarcity, and avoiding dam overtopping and failure. With the recent development of telemetred networks in Morocco, in the next following years it should be possible to implement real time quantitative flood modeling to improve dam management and safety. Therefore, there is a need to develop modeling approaches towards this objective.

Like in many developing countries, long records of rainfall and runoff data at short time steps are rarely available in North Africa (Hugues, 2011). Therefore, in the context of flood modelling, event-based models are representing a sound alternative to continuous ones. Event-based models are also often preferred to continuous models for real time operational applications in Southern Europe, however their main limitation is that the initial soil moisture conditions need be set from external information (Berthet et al., 2009; Tramblay et al., 2010). Several studies have shown the strong influence of the antecedent soil moisture conditions on the response of a catchment to a rainfall event in different regions such as Spain (Castillo et al., 2003; Rodríguez-Blanco et al., 2012), Southern France (Tramblay et al., 2010, 2011; Cousteau et al., 2012), Italy (Brocca et al., 2009a; Norbiato et al., 2008), Southwestern USA (Wagener et al., 2007), or China (Huang et al., 2007). An important research question as stated by Wagener et al. (2007) is how sensitive the model predictions of runoff are to the specification of initial wetness conditions, and how complex an inter-storm model must be to meet this requirement.

In recent studies, relationships have been established between indicators of catchment's antecedent wetness conditions and the initial conditions of event-based models. In particular, the Soil Conservation Service Curve Number (SCS-CN) method (Mishra and Singh, 2003) is widely used for operational flood modeling in Mediterranean countries (Brocca et al., 2009a, 2011b; Tramblay et al., 2010). Moreover, this model is suitable to account for initial soil moisture conditions with its S parameter describing the initial soil potential maximum retention. Several authors have successfully correlated in situ soil moisture measurements with the S parameter of the SCS-CN model for floods occurring in semi-arid environments (Huang et al., 2007; Brocca et al., 2009a; Tramblay et al., 2010). When no measurements of soil moisture are available, alternatively a continuous Soil Moisture Accounting (SMA) model can be used. This approach has been also used to set up the initial conditions of event based-models (Michel et al., 2005; Norbiato et al., 2008; Javelle et al. 2010; Cousteau et al., 2012).

In addition, soil moisture data retrieved from active and passive microwave sensors has become readily available at a temporal resolution of approximately one day (Brocca et al., 2011a). Nowadays, the most established products are those provided by the Advanced Microwave Scanning Radiometer for the Earth observing system (AMSR-E) on-board the Aqua satellite, which will be continued by the recently launched AMSR-2, the Advanced SCATterometer (ASCAT) on-board the MetOp (Meteorological Operational) satellite, and the Soil Moisture and Ocean Salinity (SMOS) mission of the European Space Agency. The various remote sensing products have been successfully validated against ground soil moisture data in different Mediterranean catchments (Gruhier et al., 2008; Albergel et al., 2009; Brocca et al., 2011a; Parrens et al., 2012). In the recent years, a growing number of studies are considering the use of this type of data to improve flood modeling and forecasting, through the implementation of data assimilation techniques (Brocca et al. 2010a, Meier et al., 2011; Matgen et al., 2012).

In this study, the feasibility of setting up a rainfall-runoff model with limited rainfall data is tested in order to reproduce the flood events occurring upstream of a large dam in Northern Morocco, the Makhazine dam. A standard event-based model is developed and tested as if it were used in an operational context. All model parameters are set as a constant for all the flood events, except for the initial condition of the model for which different indicators of antecedent wetness conditions are investigated. These indicators include antecedent precipitation and discharge indexes, as well as a simplified continuous SMA model depending on precipitation and evapotranspiration data and a single parameter. Also AMSR-E and ASCAT remote sensing data of soil moisture are evaluated for their ability to reproduce antecedent wetness conditions in the catchment. In Sect. 2 the study area and data are presented. The rainfall-runoff model is presented in Sect. 3, and the modeling results and the comparison with AMSR-E and ASCAT datasets in Sect. 4.

2 Study area and datasets

2.1 Mdouar catchment

The Mdouar catchment (65 km^2) is located upstream of the Makhazine dam (1800 km^2), the 6th largest of the country, in Northern Morocco (Fig. 1). The climate is Mediterranean, with a wet season with moderate temperatures from October to April and a hot dry season from May to September. It is also influenced by the Atlantic Ocean, 40 km downstream. The basin consists of plains in the western part, while in the east terrain becomes more rugged and mountainous. The altitude increases progressively eastward until reaching 1600 m with the foothills of the Rif mountain range. This configuration is causing large precipitation amounts in the basin, reaching up to 1100 mm yr^{-1} on average but with a strong inter-annual variability. The soil substrate consists of an alternation of marl and sandstone. The western and central parts are subject to severe erosion. The predominance of impermeable soils in the watershed is favoring runoff, which is increased by the effect of slope in the eastern part. There are neither cities nor urban centers in the catchment; vegetation is characterized by the presence of matorral, a typical Mediterranean land cover, with a predominance of cork oak forests. Most of the forest cover is located in the headwater's sub-catchments. In the lowest parts, on cultivated plains, agriculture is the dominant economic activity. The location of the basin provides a significant potential for water resources. The Makhazine dam was built in 1979 for irrigation, water supply, energy production, as well as protection against flooding of the plain downstream. It is a 67 m high dam of mixed earth and rocks creating a reservoir with a usable capacity of 724 Mm^3. The mean annual inflow is 678 $\mathrm{M\,m^3}$ and the mean evaporation is 1176 $\mathrm{mm\,yr^{-1}}$. The city of Ksar El Kebir (200 000 inhabitants) located immediately (8 km) downstream of the dam is a plain area highly vulnerable to flooding.

2.2 Precipitation and discharge data

Daily precipitation data is available for stations Makhazine dam (60 m), Mdouar (90 m), Nakhla (210 m) and Bab Taza (900 m) between 1980 and 2011 (Fig. 1). For these stations, 5 min precipitation data is also available for a few episodes. The inventory of rainfall accumulations per episodes is reported in Table 1. Total precipitation over the Mdouar catchment during the flood events was computed with the inverse distance method. There is a significant west–east gradient, with precipitation increasing from the Makhazine dam to the Bab Taza stations (Fig. 2). This gradient follows the gradual increase in altitude towards east. There is also a significant correlation in cumulative rainfall per episode between the different stations, especially between Mdouar and Bab Taza ($r = 0.96$). There is a fairly strong temporal coincidence of rainfall between the different stations: rainfall affects almost simultaneously the four stations, although stations Nakhla and Bab Taza are, respectively 67 km and 60 km away from the station located at the dam. Therefore rainfall events causing flooding in the basin have a large spatial extension. Such a configuration of rainfall fields supports the generation of potentially significant flooding, by generating runoff simultaneously in the different tributaries. However, due to the low density of rain gauge stations for such a large area it is difficult to analyze in detail the spatial distribution of rainfall intensities across the entire watershed.

Daily river discharge is measured at Mdouar since 1969 and shows a strong seasonality, with the majority of the discharge being observed during winter. 75 % of annual maximum runoff occurs during the period from December to February. No trends in extreme discharges are observed between 1969 and 2008; however there is a high variability of annual maximum daily values, between 69 and 1023 $\mathrm{m^3\,s^{-1}}$, depending on the year. Hourly discharge data is available for 16 flood events between 1984 and 2008 (Table 1) of which the vast majority occurred during winter. The base flow was extracted at the beginning of each episode, and the volume of runoff was separated from the base flow during episodes modeled by the recession model detailed in Sect. 3.1. The average runoff coefficient of all these episodes is 0.52 but it can vary between 0.19 and 0.89 giving a first indication of the high variability of the initial conditions of saturation of the basin from one episode to another.

2.3 Remote sensing soil moisture

2.3.1 ASCAT

The advanced SCATterometer (ASCAT) is a real-aperture radar instrument successfully launched on board the MetOp satellite in 2006 that measures radar backscatter at C-band (5.255 GHz) in VV polarization. The spatial resolution of ASCAT is 25 km (resampled at 12.5 km) and, for Morocco, measurements are generally obtained at least once a day. The surface soil moisture product is retrieved from the ASCAT backscatter measurements using the WARP 5.4 retrieval scheme. This method relies on a time series-based change detection approach which was previously developed for the ERS-1/2 scatterometer by Wagner et al. (1999). In this approach soil moisture is considered to have a linear relationship to backscatter (in dB), while the surface roughness is assumed to have a constant contribution in time. By knowing the typical yearly vegetation cycle and how it influences the backscatter–incidence angle relationship for each location on the Earth, the vegetation effects are removed, revealing the soil moisture variations. The derived surface soil moisture product (corresponding to a depth of 2–3 cm) ranges between 0 % (dry) and 100 % (wet) and is available for the period 2007–2011. Validation studies of the ASCAT soil moisture products assessed their reliability for estimating both in-situ and modeled soil moisture observations across different regions in Europe (Albergel et al., 2009; Brocca et al., 2010b, 2011a; Parrens et al., 2012) and also in Africa (Sinclair and Pegram, 2010), thus addressing their use for practical applications.

2.3.2 AMSR-E

The AMSR-E sensor on-board the NASA's Aqua satellite provided passive microwave measurements at 6.9 GHz (C-band) and five higher frequencies (including 36.5 GHz Ka-band) between May 2002 and October 2011, with daily ascending (13:30 equatorial local crossing time) and descending (01:30 equatorial local crossing time) overpasses, over a swath width of 1445 km. For this study, both ascending and descending passes are tested to select the configuration providing the better results. We used the AMSR-E-based Land Parameter Retrieval Model (LPRM) v5 (Owe et al., 2001, 2008) product which is produced in collaboration between the VU University Amsterdam and NASA. This product was found to provide better agreement with in situ observations than other publicly available products (e.g. Brocca et al., 2011a). LPRM is a three-parameter retrieval model (soil moisture, vegetation optical depth, and soil/canopy temperature) from passive microwave data based on a microwave radiative transfer model. It uses the dual polarized channel (either 6.9 or 10.6 GHz) for the retrieval of both surface soil moisture and vegetation optical depth. The land surface temperature is derived separately from the vertically polarized 36.5 GHz channel. Here, the gridded 0.25° soil moisture product is employed; the dataset covers the period 2002–2011. Similarly to ASCAT, also the AMSR-E-LPRM soil moisture product was extensively validated (e.g. De Jeu et al., 2008; Dorigo et al., 2010; Brocca et al., 2011a).

2.3.3 Soil water index

For many applications, the knowledge of soil moisture for a very thin surface layer is not sufficient. In this study, the semi-empirical approach (also known as exponential filter) proposed by Wagner et al. (1999) is adopted to obtain a root-zone soil moisture product (SWI, Soil Water Index) from the satellite-based surface soil moisture observations.

The SWI depends on a single parameter T (characteristic time length) which represents the time scale of soil moisture variation. The reader is referred to Wagner et al. (1999) and Albergel et al. (2009) for a detailed description of the exponential filter approach. Systematic differences between satellite-derived and modeled data of soil moisture prevent an absolute agreement between the two time series. Consequently, in this study remotely sensed data are normalized through a regression fit between satellite and modeled soil moisture values thus obtaining the SWI* index (Brocca et al., 2011a).

3 Flood modelling

This section describes the conceptual model for the Mdouar catchment. It includes several components: the base flow, the losses and the flow transfer towards the outlet. The modeling has been carried out through the Hydrologic Modeling System (HEC-HMS) software (USACE, 2010).

3.1 Base flow

A good knowledge of base flow is important to model the recession of the hydrograph and to estimate the flood volume. Here an exponential recession base flow model was selected; this approach is adequate for basins where the flood volume is strongly influenced by rainfall events (USACE, 2010).

$$B_t = B_\mathrm{i} R_\mathrm{c}^t \qquad (1)$$

With B_i ($\mathrm{m^3\,s^{-1}}$) is the initial discharge at the beginning of the simulation and R_c ([0–1]), the recession constant, describing the decay rate of the base flow. Two parameters needs to be estimated, R_c and the threshold, T_d ([0–1]), being the point in the hydrograph where base flow replaces direct runoff; it is expressed as a proportion of the peak flow of the flood.

3.2 Losses

In this study, the soil conservation service loss model (USDA-SCS, 1985) has been retained. Many studies have successfully used this model in semi-arid Mediterranean environment (e.g. Brocca et al., 2009a; Tramblay et al., 2010). Moreover, this model is suitable to account for initial soil moisture conditions through the adjustment of the parameter S, the soil potential maximum retention that can be related to various indicators of soil moisture. In the SCS model, excess rainfall is estimated based on the cumulative rainfall on the episode:

$$P_\mathrm{e} = \frac{(P - I_a)^2}{P - I_a + S} \tag{2}$$

Where P_e denotes the excess precipitation, P the total precipitation, I_a the initial losses and S the soil potential maximum retention. In the classical SCS method, the initial losses are given by $I_a = 0.2S$.

3.3 Transfer

The rainfall excess is routed to the outlet by using the Clark unit hydrograph. This method is particularly effective for reproducing complex hydrographs in basins with variable topography and land use (Sabol, 1988). The Clark unit hydrograph represents two processes: translation and mitigation. The translation is based on a synthetic time-area histogram with a time of concentration T_c (h). The histogram represents the watershed area contributing to flow at the outlet with time. Attenuation is modeled by a linear reservoir, representing the impact of basin storage, S_t (h). The average outflow of reservoir for a period t is given by:

$$O_t = C_A I_t + C_B O_{t-1} \tag{3}$$

With I_t, the inflow into the reservoir at time t, C_A, C_B, the coefficients calculated for each time step (Δt) with the equation:

$$C_A = \frac{\Delta t}{S_t + 0,5\Delta t} \text{ with } C_B = 1 - C_A \tag{4}$$

3.4 Model calibration and goodness-of-fit measures

The quantitative measure of the degree of adjustment is given by the objective function, measuring the difference between an observed and simulated hydrograph. Here the peak-weighted root mean square error (PWRMSE) was selected as objective function. It has the advantage of considering both the magnitude and time synchronization of the flood peak, by giving more weight to values of above average flow rates for a given event.

$$\text{PWRMSE} = \sqrt{\frac{\sum_{t=1}^{N} (Q_{\text{Obs}}(t) - Q_{\text{Sim}}(t))^2 \frac{Q_{\text{Obs}}(t) + Q_A}{2Q_A}}{N}} \tag{5}$$

Q_{Obs} is the observed flow, the Q_{Sim} the simulated flow at time step t, and Q_A the mean observed discharge.

The calibration process aims to find the optimal parameters to minimize the objective function. Here the method of Nelder and Mead (Rao, 1978) which uses the simplex approach was chosen to optimize the different parameters. Beside the visual inspection of simulated hydrographs, different metrics exist to measure the ability of the rainfall-runoff model to reproduce the flood events. The Nash–Sutcliffe (NS) efficiency coefficient (Nash and Sutcliffe, 1970) was used to evaluate the agreement between the simulated and the reference runoff hydrograph. In addition, the average values of the absolute errors on the estimated peak flow and volume obtained for each event were also computed to analyze the results.

3.5 Estimators of antecedent wetness conditions

Different approaches exist in the literature to estimate the S parameter for each flood event, either using base flow, antecedent rainfall, or soil moisture measured in situ or through satellites. In the classical SCS approach, the S-values are modulated based on the 5-days antecedent precipitation (USDA-SCS, 1985); however, several studies have shown that, mainly for Mediterranean catchments with a strong seasonality of the soil moisture temporal pattern, this approach was not adequate (Brocca et al., 2009a, b; Tramblay et al., 2010). In our study the calibrated S parameter is first compared to different estimators of antecedent wetness conditions, including:

1. The mean discharge over the n previous days. Since daily discharge is routinely monitored at Mdouar river section, the mean runoff averaged over several days prior to a flood event is computed, with the optimal number of days selected to maximize the correlation with S.

2. The antecedent precipitation index (API, Kohler, 1951). This index is intended to reproduce the saturation state of the basin by calculating the cumulative rainfall of previous days. The index of one day j is the index of the previous day $j-1$ multiplied by the factor k, if rainfalls occur on day j, it is added to the index:

$$\mathrm{API}_j = k\mathrm{API}_{j-1} + P_j \tag{6}$$

   The k parameter is here optimized to maximize the correlation between API and S.

3. A continuous Soil moisture accounting (SMA) model. Here a simplified version (without percolation) of the SMA reservoir of the GR4J model (Perrin et al., 2003) is used, following the same approach as Javelle et al. (2010). The SMA model computes the water level, S^*/A, of the production store of maximum capacity A,

by using daily rainfall depth over the Mdouar catchment interpolated from the rain gauges by inverse distance and the daily evaporation measured at the Makhazine dam between 1981 and 2011. The complete equations are available in Perrin et al. (2003).

4 Results

4.1 Hydrological model calibration and validation

The model structure detailed in the previous section is used to model the 16 available flood events in the Mdouar catchment (655 km^2). Due to the limited number of rain gauges, precipitation was interpolated by the method of the inverse distance to compute areal rainfall over the catchment. An hourly time step was chosen, given the observed catchment response times between 2 and 4 h, depending on the event. Since the objective is to test a model suitable for operational forecasting, it is necessary to set all parameters and provide techniques for estimating the parameters that cannot be fixed to a single value for all events. Initially, the parameters are calibrated to reproduce each flood event.

The parameters for the recession model were determined by the analysis of the recession limbs of the flood hydrographs. They are assumed constant for every flood events, since they are dependent of the morphology of the basin. The recession constant (R_c) was set at 0.75 and the threshold (T_d) to 0.3. Therefore, only the initial base flow at the beginning of each event is necessary, varying from 0.5 to 149 m^3 s^{-1} (Table 1). The parameters of the Clark hydrograph are also determined by the basin characteristics such as size, shape and topography. The values of S_t and T_c were calibrated for each episode, with different fixed S values to avoid dependencies between production and transfer model parameters. Figure 3 shows the distribution of the optimal S_t and T_c values obtained for each event. The median values of S_t = 2.5 h and T_c = 4.1 h are suitable for most episodes, except for two events (29 January 1986 and 21 February

1987) for which the calibrated S_t values are exceeding 4. However, for these two events the model simulations are not very sensitive to the values taken by this parameter. On the contrary, a preliminary analysis has shown that the flood simulations were much more sensitive to the S parameter.

The S parameter, representing the deficit of water storage in the basin prior to an event is also calibrated for each episode. The optimized values of S for each event ranged from 157.8 mm to 273.3 mm, indicating a wide range of initial conditions of soil saturation at the beginning of the events. Figure 3 shows a great variability in the calibrated values of the S parameter, indicating that a single mean – or median – value of the S parameter may not be adequate for most of the events. The calibrated S parameter values have been related to the different estimators of antecedent wetness conditions (Fig. 4). The optimal relationship between S and the discharge of the previous days was obtained when averaging the discharge over 6 days prior to the flood event dates (thereafter Q6J), with $R^2 = 0.67$. Similarly, the optimal relationship between S and API was obtained for $k = 0.98$, with $R^2 = 0.82$. By comparison, if using the cumulative rainfall 5 days prior to the flood events, adopted in the classical formulation of the SCS-CN method, $R^2 = 0.19$. Finally, the best relationship is obtained with the S^*/A level of the SMA store, for $A = 218$ mm, leading to a $R^2 = 0.90$.

The model performance obtained with the S parameter calibrated for each event is shown in Table 2, leading to a mean Nash value of 0.81. The observed and simulated flood hydrographs are displayed in Fig. 5. For some events the flood peaks are underestimated most certainly because of the uncertainties on rainfall over the catchment; rainfall is indeed the most critical input for flood modeling (Andréassian et al., 2001). However, despite some discrepancies, the model is able to reproduce well the flood dynamics at the hourly time step. The model is then validated as if it were used in an operational context. The recession and transfer parameters are considered fixed, with only the S parameter varying for each event. A resampling procedure was implemented; for the n flood events, each event i was successively removed and the relationship between S and the three different antecedent conditions estimators was re-estimated using the remaining $n-1$ episodes. The S value obtained by this procedure was then used to model the flood event i, and the simulated discharge was compared to the observed discharge. This approach provides insight into the uncertainties on many episodes, and thus evaluates the performance that the model could have with new episodes. Results are presented in Table 2, indicating a better model performance in validation to reproduce the flood events when using the SMA model to estimate the S parameter values.

4.2 Antecedent moisture conditions from remote sensing data

Finally, the capability of the two satellite soil moisture products derived by ASCAT and AMSR-E sensors to reproduce the modeled soil moisture data with the SMA approach was analyzed. In particular, the comparison was shown between the normalized SWI, SWI*, and modeled data both considering the relative soil moisture values and their anomalies. We note that the comparison considering the anomalies is more robust as the strong seasonality of soil moisture could artificially produce high correlations (Albergel et al., 2009). Anomalies were computed as in Albergel et al. (2009) by considering a 5-week sliding window. For the computation of the SWI, the T parameter of the semi-empirical approach by Wagner et al. (1999) has to be estimated. It was obtained here by maximizing the correlation between satellite and modeled data considering the whole dataset, i.e. 2002–2011 for AMSR-E and 2007–2011 for ASCAT. The obtained T-values are found to be equal to 26 and 15 days for ASCAT and AMSR-E, respectively, in accordance with the results obtained by Brocca et al. (2010a) who contrasted modeled and ASCAT-derived soil moisture data for several catchments in Central Italy.

Figure 6 shows the comparison between modeled, S^*/A, and satellite soil moisture data for the period 2007–2011 for which both products are available while Table 4 summarizes all the comparisons in terms of correlation coefficient, R, and root mean square error, RMSE. As it can be seen, the performance of both satellite products in the period 2007–2011 is high with R-values equal to 0.974 and 0.916 for ASCAT and

AMSR-E, respectively. Also the comparison in terms of anomalies provide satisfactory results with R-values higher than 0.73. For AMSR-E, even considering the whole period 2002–2011 (10 yr) the performance is still good. The good agreement between satellite and modeled data gives a clear indication about the possibility to use this data source for the estimation of the antecedent moisture conditions to be used for the initialization of the rainfall-runoff model. This approach could be really effective as long-term time series of rainfall and evaporation (needed to run the SMA model) are not required anymore.

5 Conclusions and perspectives

An event based rainfall-runoff model has been developed in a Moroccan catchment located in the north of the country. The model was found to be able to reproduce the flood events at an hourly time step, even if only a limited number of raingauges is available over the catchment. Different estimators of the antecedent wetness conditions of the catchment were tested, the best results were obtained with a daily soil moisture accounting (SMA) model. In addition, two different satellite soil moisture products were tested (ASCAT and AMSR-E) and both were able to reproduce with satisfactory accuracy the daily soil moisture dynamics simulated by the SMA model. Therefore this study demonstrates the feasibility of rainfall-runoff modeling at sub-daily timescales in Northern Morocco. With the current deployment of automatic telemetred stations in several river basins of Morocco, this approach could be useful to set up real-time monitoring systems to improve dam management. The approved continuity of the satellite missions (AMSR-E will be shortly followed up by the recently launched AMSR-2 onboard GCOM-W1 while MetOp-B/ASCAT will be launched in autumn 2012) guarantees that such a service can be continued operationally at least until 2020.

If more data would be available, we could also test continuous models to compare the simulation results. The model efficiency could be improved by increasing the knowledge of the rainfall amounts intercepted by the catchment during the flood events. This could be accomplished by the installation of additional rain gauges, in particular in the most elevated areas. Another option would be to consider spatial rainfall data that could be provided by the meteorological radar recently installed in the city of Larache (50 km downstream). Further studies should focus on the applicability of such models in a regional context, by providing guidelines of application in the case of partly gauged or ungauged catchments. The good relationships obtained between satellite data and modeled soil moisture provides insights for further research on different catchments in Northern Africa to palliate the lack of ground measurements.

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Table 1. Flood events characteristics.

Dates	Baseflow ($m^3 s^{-1}$)	Maximum discharge ($m^3 s^{-1}$)	Maximum 1 h rainfall (mm)	Duration (h)	Runoff coefficient	Mdouar catchment precipitation average (mm)	Precipitation totals (mm)			
							Dam	Mdouar	Nakhla	Bab Taza
18 May 1984	149	540	7.1	37	0.34	61.6	18.6	56.4	43.1	72.3
26 Nov 1985	77	644	7.9	49	0.19	77.4	42.8	77.7	–	82.8
1 Jan 1986	18.3	366	6.2	27	0.38	20.5	0.7	19.3	6.3	21.7
29 Jan 1986	3	546	6.3	50	0.48	69.9	9	54.2	39.6	87.5
31 Jan 1986	73.3	287	3.8	70	0.68	31.0	–	41.8	21.4	20.7
17 Feb 1986	149	528	6.1	56	0.78	31.6	–	28.8	–	34.5
20 Feb 1986	95.7	406	4.2	33	0.69	16.5	1.5	15.5	–	17.4
7 Mar 1986	25.4	603	7.6	39	0.67	32.7	22.3	42.3	20.3	25
12 Jan 1987	102.8	762	7.8	45	0.33	103.5	43.5	81.5	63.8	129.1
29 Jan 1987	7	1110	12.0	80	0.64	180.7	80.8	145.6	83.7	215
21 Feb 1987	60.8	550	5.9	82	0.81	55.0	24.7	44.4	–	72.6
3 Dec 1987	41.6	464	7.3	41	0.24	52.2	25.3	35.8	12.5	68.3
27 Dec 1995	20	720	12.8	21	0.47	52.3	–	52.8	–	–
14 Nov 2002	0.5	763	16.0	22	0.34	75.6	–	75.6	–	–
8 Dec 2003	61	1355.1	8.8	47	0.89	66.8	–	66.8	–	–
29 Nov 2008	19	308.7	13.0	17	0.28	28.2	–	28.2	–	–

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Table 2. Model calibration and validation results.

		Total runoff			Direct runoff		
		NS	ErrQp	ErrVol	NS	ErrQp	ErrVol
Calibration		0.81	0.18	0.09	0.83	0.19	0.11
Validation	LogQ6J	0.66	0.27	0.19	0.68	0.29	0.26
	API	0.70	0.27	0.18	0.73	0.29	0.25
	SMA	0.71	0.25	0.19	0.75	0.27	0.26

NS: mean of NS-values for each event.
ErrVol: mean of absolute values of volume error for each event.
ErrQp: mean of absolute values of peak discharge error for each event.

Table 3. Summary of the performance of the two satellite soil moisture products for estimating the data modeled through the SMA model.

Period	2002–2011			2007–2011		
Score	*R*	RMSE	*N*	*R*	RMSE	*N*
ASCAT	–	–		0.974	0.071	1437
ASCAT anomalies	–	–		0.743	0.45	1437
AMSR-E	0.914	0.122	2243	0.916	0.122	1192
AMSR-E anomalies	0.659	0.555	2243	0.734	0.483	1192

R: correlation coefficient.
RMSE: root mean square error.
N: sample size.

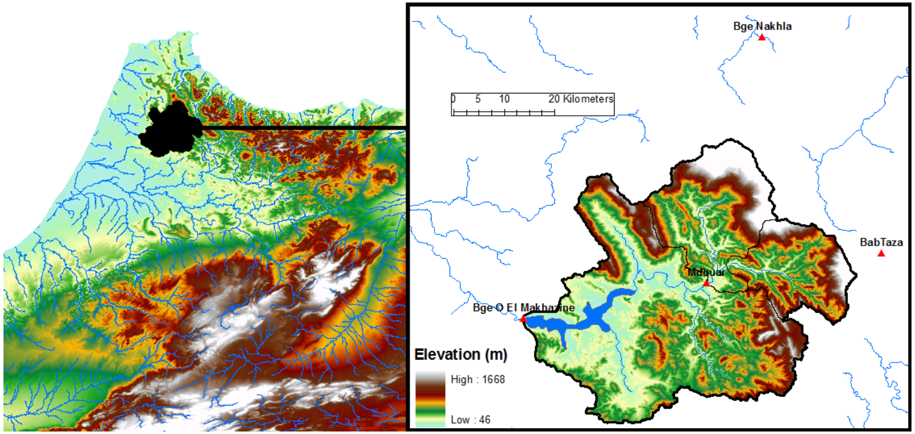

Fig. 1. Catchment and rain gauges stations.

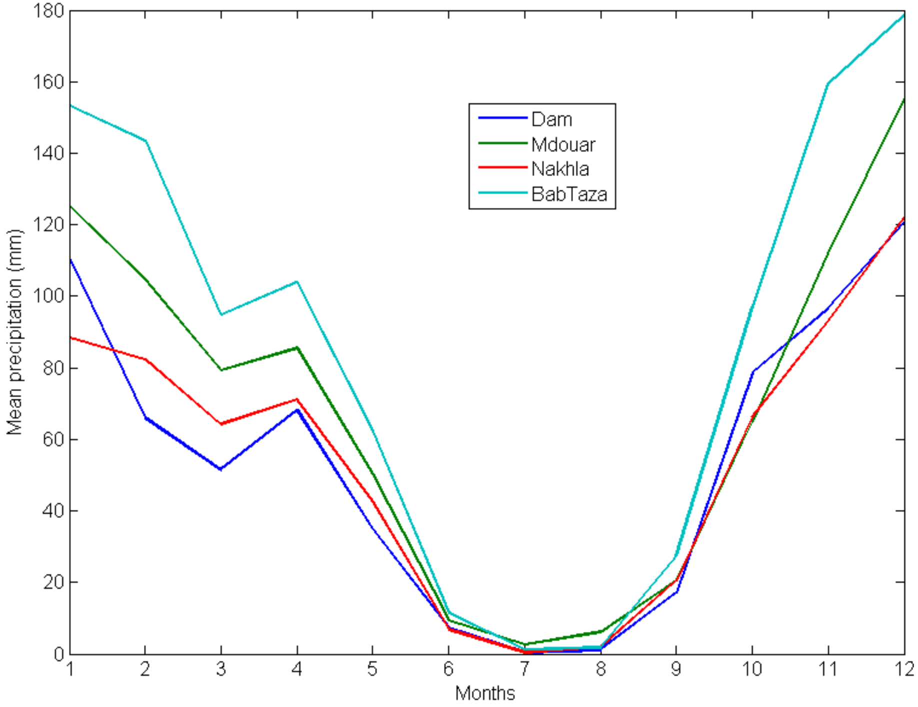

Fig. 2. Monthly mean precipitation (1980–2010) in the different stations.

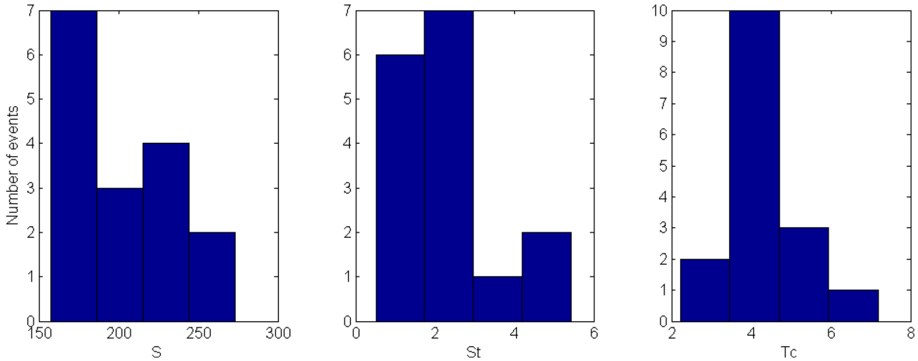

Fig. 3. Distribution of the calibrated model parameters S, S_t and T_c.

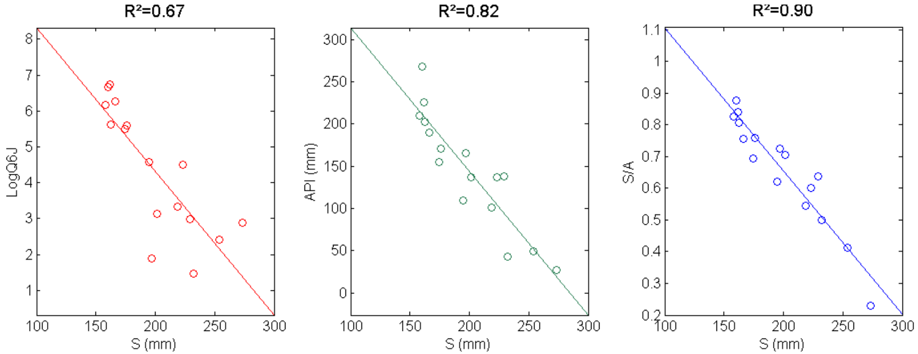

Fig. 4. Relationships between S and the antecedent wetness conditions indicators, LogQ6J, API and S^*/A.

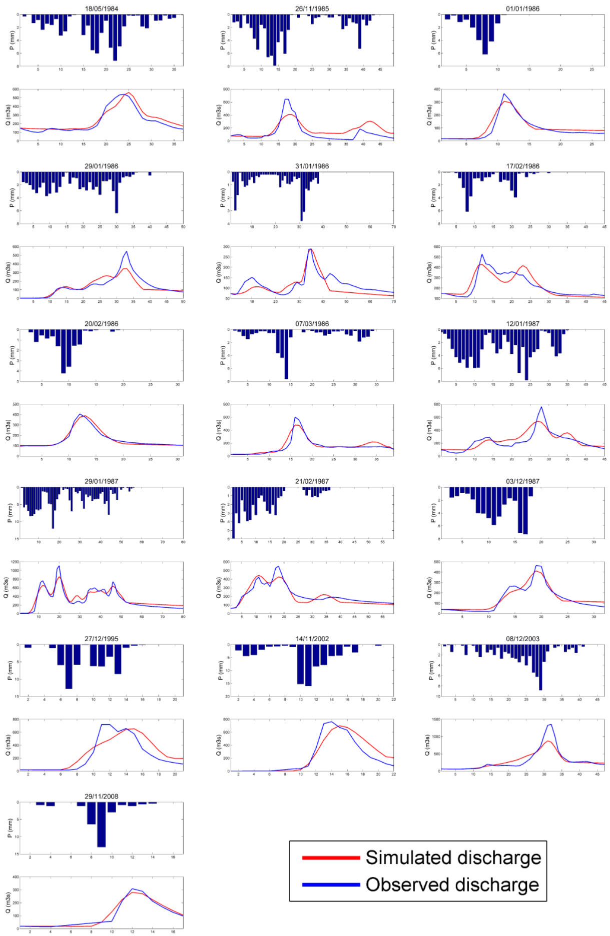

Fig. 5. Observed and simulated hydrographs at the hourly time step.

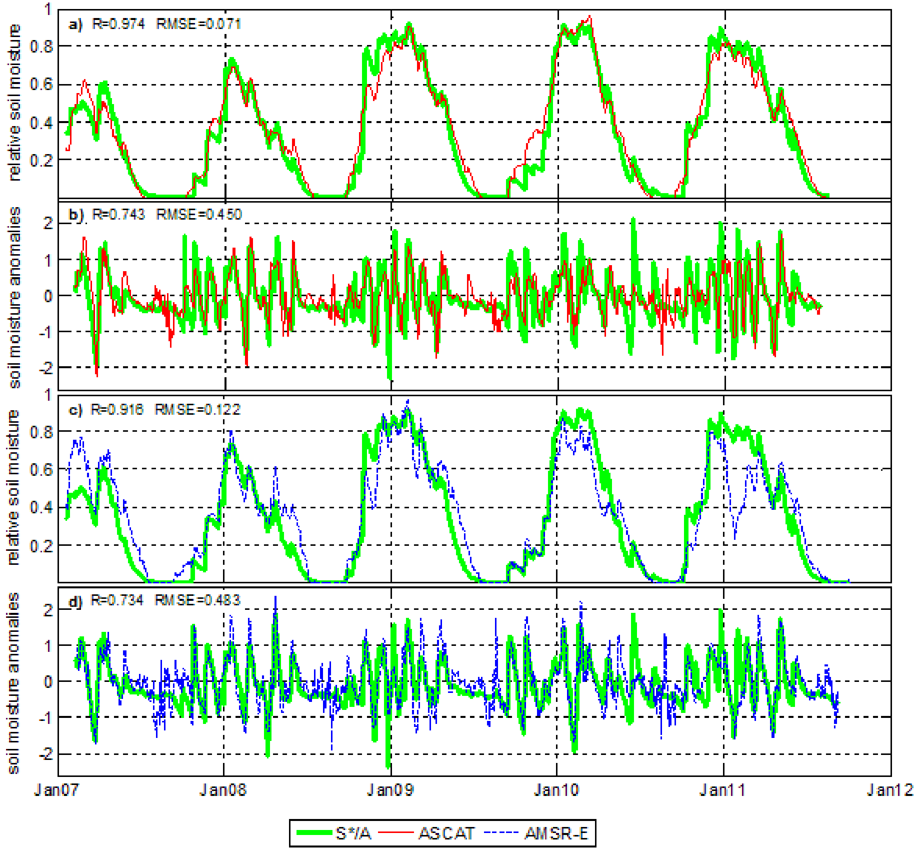

Fig. 6. Comparison between modeled relative soil moisture data, S^*/A, and the two satellite soil moisture products, ASCAT and AMSR-E, for the common period 2007–2011. **(a, c)** relative soil moisture values, and **(b, d)** soil moisture anomalies.