An integrated geomorphological and hydrogeological MMS modeling framework for a semi-arid mountain basin in the High Atlas, southern Morocco

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Abstract: The aims of this study are to develop and implement a precipitation-runoff model in the Modular Modeling System (MMS) for a small mountain catchment, the Ameskar basin. It is part of the meso-scale, semi-arid Drâa basin investigated within IMPETUS, an integrated project for the efficient and sustainable use of freshwater in southern Morocco. The River Drâa drains from the High Atlas Mountains to Lac Iriki and feeds a large dam for irrigation purposes. Precipitation inputs include rain and snow from 3 climate stations. Snow sublimation plays a significant role in the higher altitudes and is integrated accordingly. Vegetation is scarce outwith the intensively irrigated oases and evapotranspiration is limited to small shrubs. Surface run-off and springs are controlled by complex geomorphological and geological settings and by highly porous, infiltrating wadi river beds. The MMS model has been developed mainly on the basis of geomorphologically and hydrogeologically defined Hydrological Response Units (HRUs). Discharge is sporadic, extreme and varies according to snowmelt and precipitation. Infiltration dominates over surface discharge and is important for groundwater renewal especially in limestone and basalt. MMS will be developed for the whole Drâa catchment for operational discharge forecasting in future.

***Keywords**:* MMS, Hydrological Response Units, semi-arid, mountain

1. INTRODUCTION

Mountains play an important role in the regional water balance of large, complex, semi-arid basins [Cunningham et al 1998, Flerchinger and Cooley, 2000, Khazaei et al 2003, Pitlick 1994, Salvetti et al 2002, Viviroli et al 2003]. However, the contribution of snow and rainfall to the annual and multi-annual water balance in remote high mountain regions in north-western Africa is largely unknown [Matthews 1989 et al]. This study aims to investigate the water balance of the semi-arid Ameskar catchment in the High Atlas Mountains based on an integrated geomorphological and hydro-geological MMS (Modular Modeling System) framework.

2. STUDY AREA

The study site is the remote, semi-arid Ameskar basin located in the northern Drâa basin within the M'Goun Range (3950 m) of the High Atlas Mountains (Figure 1). Here, the High Atlas forms a Mesozoic calcareous massif. The catchment consists of complex, highly folded geological units, mainly limestone, basalt, syenite, Quaternary cinder, silt, sandstone and gypsum. Geomorphologically, the basin has rockfaces, extensive scree slopes, debris flow channels, debris fans, ancient and active landslides on the lower valley flanks and coarse, gravelly river beds. The Assif-n-Ait-Ahmed flows over a highly porous bed with an average surface discharge of only 0.5 m^3s^{-1} and sporadic flow down to the village of Lower Ameskar. Flow becomes totally subsurface in the lower reaches of the valley. The Assif-n-Ait- Ahmed joins the M'Goun which in turn forms the Drâa below its confluences with the Dades [Youbi 1990]. At Ifre (1500 m) average discharge is 4 m/s. Vegetation in the valley is scarce and dominated by scattered juniperus trees between 1800-2400 m, cushion shrubs above 2400 m and accacia wadi communities in the rivers and dry wadi beds. These are partially irrigated with Mediterranean fruit oases

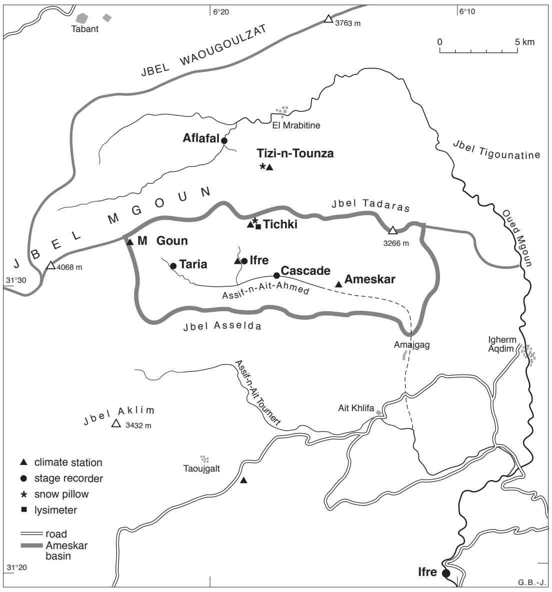

Figure 1 Map of Ameskar study basin in the M'Goun range with stream gauges and climate stations

and legumes. In the Upper Drâa, the average annual available groundwater resource is approximately 80 Mm^3 per annum. At Ifre, the Oued M'Goun has a catchment size of 1240 km^2 and although it covers only 8% of the total surface area of the Upper Drâa it provides the main freshwater resource for the region.

2.1 Climate

The High Atlas mountains play a distinct role in producing orographic precipitation and cloud formation. Average annual precipitation in the Ameskar catchment varies around 500 mm and is influenced by a strong vertical temperature and rainfall gradient. The semi-arid climate can be subdivided into two dominant seasons: a wetter winter season with both rain and snow at the beginning and towards the end and a very dry summer season with at least 2 months without precipitation. At the highest peak station (3850 m) minimum temperatures can reach –25°C during the winter while average summer temperatures only reach 15°C and wind speeds can attain 25 m/s. On average there are more than 140 frost days per year. Snowfall events are erratic throughout the winter and at the higher stations, first modeling results and field experiments indicate a high percentage of snow lost directly through sublimation [Schulz et al 2003].

2.2 Flood hydrology

Sporadic floods occur as a result of snowmelt and / or catchment wide precipitation in spring and autumn (Figure 2). The flood characteristics are a

Figure 2 Rapid surface flow over basalt with flood in confluence of the main channel, Sept. 2003 [Foto: Cappy]

reflection of extreme rainfall or snowmelt patterns as well as geomorphologic and geologic setting. Flood peaks are high with steep ascending and descending ("shark-tooth") flood limbs. The periods between extreme events are marked by low or absent discharge.

2.3 Hydrogeology and Geomorphology

The Ameskar basin can be roughly divided into two main geological units, the massive limestones and dolomites that shape the higher levels of the catchment and the basalts covered by clays along the lower slopes (Table 1). The karstic aquifers have a transmissivity of between 10^{-1} to 10^{-4} m^2/s and are therefore highly permeable. Since scree slopes are extensive in the limestones, large amounts of water can infiltrate easily into the underground.

Table 1 Hydrogeological characteristics of Ameskar basin [Reichert, Cappy and Thein 2003]

Formation	Lithology	Classification
Quaternary	sand, gravel, limestone clasts	porous aquifer / 0 to 30 m / 10^{-2} m.s^{-1} porous aquifer / 20 to 50 m/ 10^{-3}m.s^{-}
Liassic *(carbonatic)*	limestone, dolomite	porous and fractured aquifer to a karst aquifer / 100 to 500 m / 10^{-6} to 10^{-2} m.s^{-1}
Liassic *(siliciclastic)*	sandstone, limestone, dolomite	fractured aquifer / 20 to 50 m / variable
Lower Liassic /Upper Triassic	clay, siltstones	aquitarde / < 5 m / 10^{-9} m.s^{-1}
Triassic *(basalt)*	doloritic basalt	Fractured aquifer / 50 to 300 m / 10^{-8} to 10^{-3} m.s^{-1}
Triassic *(continental)*	sand-siltstone, conglomerates	Aquiclude < 200 m / 10^{-6} m.s^{-1}

The recession coefficient of the slow discharge components lies between 120-210 days in limestone aquifers [Schwarze et al 1999]. The clay sediments of the Upper Trias form a near impermeable layer with a clear spring horizon. Triassic basalts are densely developed with fissures of different transmissivity ranging between 0.15-1.5 10^{-7} m^2/s according to Schwarze [1999] and have a recession coefficient of 270-310 days. The hydrogeological situation of the basin can only be roughly estimated at the moment with the help of tracer and dating techniques.

The basin can be subdivided into several geomorphological units based on the underlying geology and geomorphologic activity. The main units in the highest regions consist of old terraces and erosional surfaces that are highly permeable and contain loose rock fragments. The most widespread units in the catchment are the screes that cover the steeper slopes below the rock faces. The scree slopes are fed by rock falls originating are preferentially reworked by a dense network of debris flows. The scree slope units also have a high permeability and they often consist of moist soils covered by a protective layer of rock fragments. Some of the lower slopes are covered by cinder slopes. This unit is totally impervious due to their clay content but can be found in close vicinity to the highly pervious units. The next category are the river beds themselves and the fluvially eroded lower slopes. The river beds consist of a massive layer of loose stones and rocks reworked by rare flood events or deposited at the lower valley slopes as debris fans. They are highly permeable unless in contact with rock layers near the surface as is typical for basalt dykes. The last category consists of mass movements. These are also located along the lower valley slopes but are of much larger extend and volume. They are reworked finer sediments and are less permeable than the adjacent river beds or slopes.

3. METHODOLOGY

3.1 Climate stations

In the Ameskar catchment, climate stations were installed at three sites (Figure 1): Ameskar (2250 m), Tichki (3260 m) and M'Goun (3850 m). Since 2001 common meteorological data include soil and air temperature, humidity, radiation, precipitation, wind direction and wind speed is collected at one level in 15 minute intervals.

3.2 Discharge Stations

Three float gauge stations are operational in the catchment (Figure 1), one since April 2002 in Taria (2752 m) with a catchment area of 5.5 km^2, one since October 2003 at Cascade (2195 m) with a catchment area of 53 km^2 and one since November 2003 at Tichki village with a catchment area of 15 km^2. Serious problems were encountered with discharge measurements due to very long periods of low flow alternating with extreme flood flow. Since no calibrations were possible during high / flood flow, discharge is underestimated for floods especially at Cascade where the flow cross-section is difficult to define. During the period of 2002, the Taria stage recorder periodically stopped working over the summer of 2002 and after the flood in April 2003. This is possibly caused by high suspended sediment concentrations deposited on the wheel during the flood and causing the float to jam. The observed stage was corrected manually for this second period according to the pre-flood reference level.

3.3 Geological and hydrogeological mapping

A detailed geological map was produced by a combination of field work and image interpretations derived from remote sensing. Hydrogeological measurements distinguished the discharge of different springs, the age and origin of water. The methods include δ^2H, $\delta^{18}O$ and Tritium measurements, discharge and water quality measurements of springs.

3.4 Geomorphological mapping

The geomorphology of the basin was determined from field work, topographical maps (1: 100 000) as well as from high resolution remote sensing images such as IKONOS and ASTER (Figure 3).

3.5 Soil water investigations

Soil water investigations included sprinkling and infiltration experiments as well as studies on the structure and skeletal content of soils. Diverse units were studied such as the highly permeable river beds, impermeable cinder slopes and widespread scree slopes.

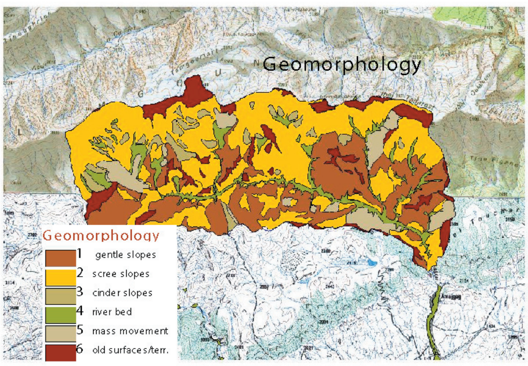

Figure 3 Detailed geomorphological basin map

4. MMS MODEL

4.1 GIS Weasel

The pre-processor for the Modular Modeling System (MMS) model consists of the GIS Weasel which is a GIS-based tool for classifying Hydrological Response Units (HRUs) based on a Digital Elevation Model with a grid size of 100 m, vegetation maps derived from topographical maps and remote sensing images, geomorphological, geological and simple assumptions derived from soil characteristic maps (Figure 4). All units were digitized as polygons and converted into grids as a basis for parameterization for the MMS model. HRUs were disaggregated to improve discharge modeling [Carlile 2002].

The catchment was subdivided into two main zones: the Taria subcatchment at the Taria gauging outlet and the Cascade subcatchment at the Cascade outlet. No surface discharge is present at the final basin outlet therefore the model was not run for that part.

4.2 MMS Model

The PRMS (Precipitation Runoff Modelling System) developed by Leavesley [2002] was applied for the Ameskar catchment. It includes a special function for precipitation that allows precipitation to be extrapolated between the different stations for individual HRUs. Precipitation (including snow and snow water equivalent) from the three stations is computed for the HRUs according to the daily

a)

b)

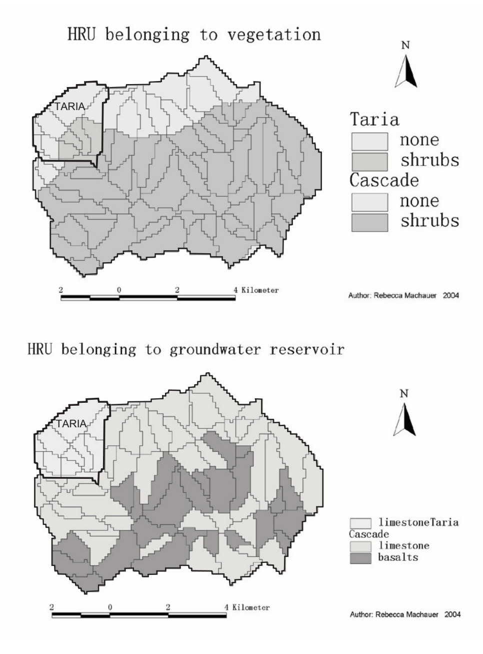

Figure 4 Taria and Cascade subcatchments with HRUs for a) vegetation [after de Jong 2003] and b) hydrogeology [after Bell 2003, Budewig 2003, Hofmann 2002, Osterholt 2002 and Cappy 2003]

measured minimum and maximum temperatures and radiation. This is particularly important for mountain basins with highly variable precipitation. Precipitation was corrected for the three stations according to Sevruk and Zahlavova [1994]. The modeled discharge results for Taria and Cascade are decomposed into several water balance components (Table 2). Comparison of the modeled results of the Taria subcatchment shows that a large percentage of the water is transmitted into storage and base flow (nearly 40%) and that there is nearly twice as much subsurface flow as surface discharge. This is due to the fact that, geologically, the whole sub-catchment consists of limestone. In Cascade, on the other hand, a very high percentage of precipitation is lost by evaporation and by sublimation after snow events. Less than 15% of the flow is subsurface and less than 11% is surface discharge.

Table 2 Modeled components of water cycle for a) Taria subcatchment and b) Cascade subcatchment [after Machauer 2003].

	N	ETA	Q	Q_O	Q_I	Q_B	S
a) mm	569	20	123	6	9	110	101
%	100	38.7	21.6	1	1.6	19.3	17.7
b) mm	384	281	42	6	7	15	33
%	100	73	11	1.6	1.8	3.9	8.8

N = total precipitation, ETA = actual evapotranspiration, Q = discharge, Q_O = surface flow, Q_I = interflow, Q_B = base flow, S = storag

Whereas interflow exceeds surface flow for most of the flood events and for average flow at Taria, surface flow equals or exceeds interflow at Cascade. This is mainly due to the geomorphological setting of the basin. The highly porous channels of Taria and Cascade are rapidly filled with water during heavy and intensive precipitation events, such that surface flow peaks rapidly over short periods after the interflow storage areas have been saturated. Flood recession is equally rapid, producing the characteristic "shark-tooth" flood hydrograph. Once the precipitation input ceases, which is very abrupt in these regions, flow retreats rapidly into the interflow areas which in turn feeds into the deeper groundwater reservoirs. Thus high flow and flood flow events reflect a high percentage of near surface and surface flow. Since the vegetation cover is sparse and loamy soils are rare, little water is buffered in the vegetation zone.

These first results show good correlations between the modelled and observed discharge and are promising given the complexity of the catchment geology and the short climate and discharge time series involved (Figure 5). For the Taria subcatchment the Pearson correlation coefficient between modeled and observed discharge is 0.74 and the Index of Agreement is 0.70. The differences between the observed and simulated runoff for Taria and Cascade are the result of different processes in each basin, for example the timing and magnitude of runoff reflects precipitation versus snowmelt. Thus the lower flow on the 4th of April at Taria is the result of snowmelt initiated 4 days after the precipitation event. At Cascade, the same event causes an earlier and higher modeled flood peak as a result of immediate rainfall runoff response. The flood event is considerably overpredicted but considering that the observed discharge is not totally reliable at this site, the modelled discharge may, in this case, be a better approximation of the real situation. The rapidity of development and decay of flood peaks is a reflectance of both the high porosity of the wadi river beds and the karstic nature of the region.

a)
b)

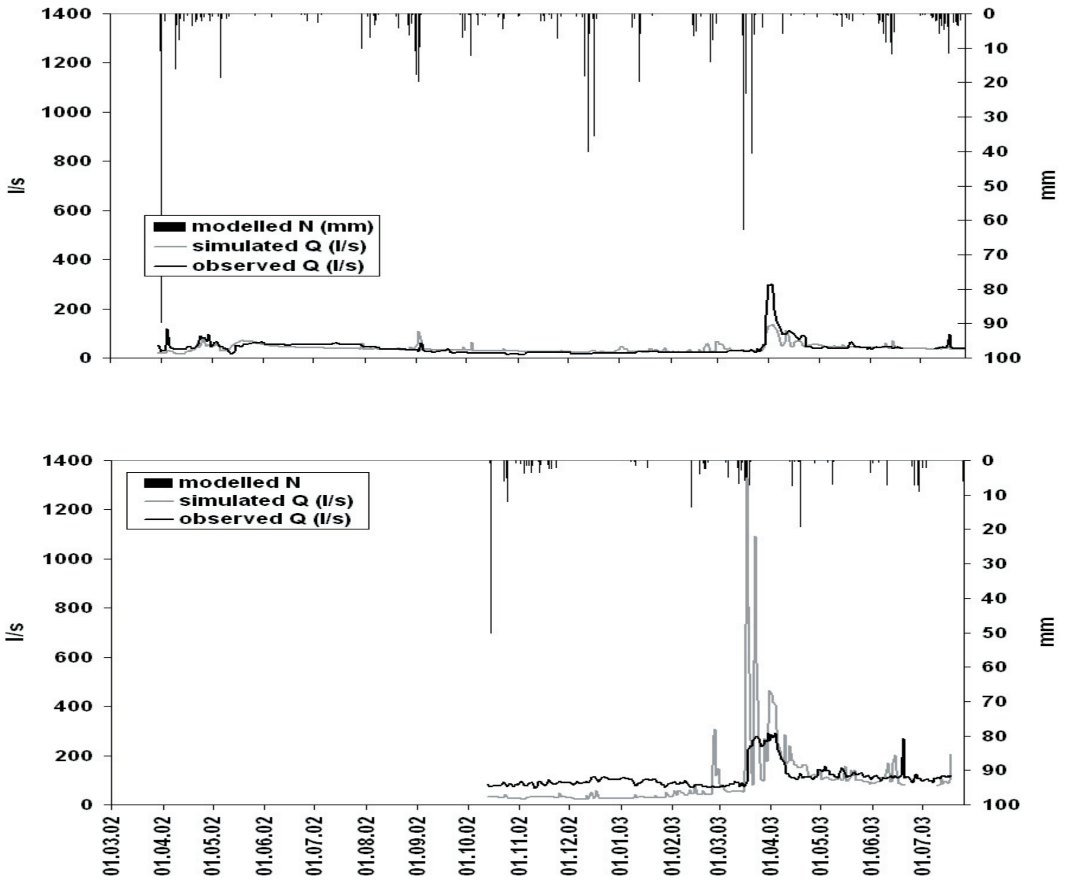

Figure 5 Modeled versus observed results for a) Taria and b) Cascade subcatchment (Oct. – July 2003).

5. CONCLUSIONS

This study shows the benefits of application of the Modular Modeling System in a small, complex, mountainous catchment. The modeling procedure has given insight into the complexity of discharge patterns in semi-arid mountain basins. A major focus was put on the identification and parameterization of Hydrological Response Units based specifically on their geomorphological and hydrogeological characteristics. The model results show that discharge reacts more sensitively to precipitation than to the hydrogeological components.

There are two main conclusions that can be drawn from this study. Firstly, the climatological, geomorphological and geological characteristics as well as gauging errors of the two basins can explain the differences between the simulated and observed discharge. The dominance of snow over rainfall, the differences between limestone versus basalt aquifers and the percentage of porous river beds all influence the timing and magnitude of flow. In future, it is desirable to develop a channel loss function for the model to analyze the overestimation in rainfall runoff. Secondly, specific discharge components should be developed in cooperation with hydrogeologists. Observations of flow and chemistry will improve the knowledge of flow paths and residence times of water in the basins and this knowledge will be used to improve the model. It is also anticipated to validate the high ETA in relation to discharge.

6. ACKNOWLEDGEMENTS

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