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Cumulative influence of small reservoirs on downstream flows in a semi-arid catchment: Merguellil, central Tunisia

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Abstract Despite small reservoirs becoming increasingly widespread across many semi-arid regions, their cumulative influence in large catchments remains poorly understood. Part of the difficulty lies in distinguishing their effect over concurrent human and climatic processes which also affect runoff. In the Merguellil catchment, in semi-arid central Tunisia, detailed analysis of 114 events revealed a 45% decrease in the runoff coefficients of rainfall events under 40 mm occurring on similar conditions of land cover and soil humidity, following the development of reservoirs and contour benches. These are capable of reducing annual flows by 25–30%. However the major decrease in catchment runoff observed after their construction is shown to be largely related to climatic fluctuations. Annual runoff variations were weakly correlated with total rainfall, but driven by changes in the number of rainfall events over 15 mm (5–6 per year) and in their circumstances, notably rainfall intensity, crop cover and antecedent soil moisture.

Key words small reservoirs; water harvesting; runoff coefficients; rainfall events; climate influence; semi-arid zones

INTRODUCTION

In the Mediterranean, water and soil conservation techniques have evolved since Roman times in an attempt to reduce soil loss and silting of downstream dams, harvest scarce and unreliable rainfall for local users and in certain cases recharge groundwater (Talineau *et al.*, 1994). Techniques notably consist of contour benches that slow and reduce transport of eroded soil, and small reservoirs that retain river flows and sediment. Driven by support from governmental and international projects, water and soil conservation works (WSCW) have become increasingly widespread (Nyssen *et al.*, 2010; Bouma *et al.*, 2011), as a solution against high spatio-temporal rainfall variability, prolonged droughts and soil erosion (García-Ruiz *et al.*, 2011).

By capturing upstream runoff, these structures modify the spatio-temporal distribution of water resources, notably increasing evaporation and in certain cases, groundwater recharge. Several studies based on hydrological measurements and geochemical analyses calculated their water balance at a local scale (Gay, 2004; Li & Gowing, 2005; Al Ali *et al.*, 2008; Al-Seekh & Mohammad, 2009) but their cumulative influence in catchments over 100 km^2 remains poorly understood (Kongo & Jewitt, 2006; Lacombe *et al.*, 2008). At a large scale, their influences become difficult to distinguish from other concurrent, variable and mutually dependent processes (Cudennec *et al.*, 2004), which also affect the hydrological behaviour of the catchment: rainfall spatial variability, soil moisture, land use and land cover changes, and groundwater interactions.

Past studies have shown a reduction in downstream flows consecutive to the construction of several WSCW (He *et al.*, 2003, Nyssen *et al.*, 2010), but contradictory results in the Tunisian Merguellil catchment of a reduction ranging between 1% and 50% illustrated the complexity and uncertainties in upscaling the influence of individual structures (Dridi, 2000; Kingumbi, 2006; Lacombe *et al.*, 2008; Abouabdillah, 2010). Studies relied on identifying changes in runoff coefficients from field measurements before and after WSCW development (Dridi, 2000; He *et al.*, 2003; Lacombe *et al.*, 2008; Al-Seekh & Mohammad, 2009), or conversely accounting for the many variables and their interactions driving the hydrological processes in a semi-arid basin (Cudennec *et al.*, 2004; Kingumbi, 2006; Ma *et al.*, 2010).

By better accounting for the limited number of rainfall events and the influence of their characteristics (rainfall intensity and volume, soil moisture and land cover) on runoff coefficients (R_c), this study seeks to improve the understanding of the catchment's hydrological response over the period of WSCW development. Their influence will be isolated in the residual anomalies of R_c for rainfall events of similar characteristics. The role of climatic changes on observed annual runoff variations will also be highlighted.

MATERIALS AND METHODS

Small reservoirs in the Merguellil upper catchment

The case study area is the Merguellil upper catchment (1183 km^2) located in the central semi-arid part of Tunisia, and whose downstream outlet is the El Houareb dam built in 1989. Average rainfall is low (265–515 mm/year increasing with altitude, Lacombe *et al.*, 2008) and characterised by high annual and interannual variability (329 mm/year ± 131 mm) and intense events (up to 50 mm/h) during autumn and spring, which cause wadis to overflow. Altitude varies between 200 m and 1200 m and average temperature is 19.2°C (10.7°C in January and 28.6°C in August, with a total potential evapotranspiration of 1600 mm/year). Land use is dominated by traditional Mediterranean crops suited to the extended dry season, mostly cereals (30% of catchment surface area) and fruit trees (20%), especially olive groves. Grasslands cover 30%, forest 19% and towns and water courses the remaining 1% (Dridi, 2000).

The catchment contains several water and soil conservation works built since the 1960s with the support of several governmental and international projects. Fifty small reservoirs drain 20% of the basin and have a combined capacity of 5.8 hm^3, capable of containing a third of the average annual runoff. Of these, 30 reservoirs were built during the 1990s after the construction of the El Haouareb dam, partly to reduce silting. Contour benches cover 27 000 ha and together these structures control runoff from 28% of the catchment surface area. However, by trapping sediments, these structures lose part of their capacity each year; 4.6%/year for reservoirs (Ben Mammou & Louati, 2007) and 3%/year for contour benches (Baccari *et al.*, 2008). These inventories were based on previous work (Dridi, 2000; Lacombe *et al.*, 2008) and updated through field surveys, and satellite imagery (SPOT 2.5 and 10 m panchromatic images and Google Earth). The Modified Normalised Difference Water Index (Xu, 2006) which exploits the reduced reflectance in the Medium Infrared spectral bands was also used in the first instance to detect flooded reservoirs (>1 ha) on 30 m Landsat images.

Hydro-meteorological data and runoff coefficients analysis

The width of the riverbed at the outlet, as well as important surface–groundwater interactions, prevent the direct measurement of the catchment runoff. This was instead estimated from the El Haouareb dam water balance using daily stage, rainfall and evaporation measurements, as well as estimations on withdrawals and releases provided by the Tunisian Ministry of Agriculture. Stage heights are converted to surface areas and volumes using standard curves revised following the levelling surveys carried out in 1989, 1994, 1997 and 2006. Infiltration was estimated using a dynamic value, set according to the water level in the fissured aquifer on which the dam sits. Estimations remain subject to errors, notably from the rating curves and uncertainties in the various fluxes (Kingumbi, 2006; Alazard *et al.*, 2011). The hydrological year spanning from September to August was used for annual studies.

Rainfall was interpolated from daily time series for a network of 80 raingauges, scattered in and near the catchment borders, using Inverse Distance Weighting (IDW). By defining fixed coefficients, this commonly used method benefits from reduced calculation times when interpolating daily rainfall precipitation over 50 years. The dense and homogeneous rainfall observation network implicitly integrated altitudinal precipitation gradients (Feki *et al.*, 2012) at the spatial and temporal scales used in this study. The SPATIAL module of Hydraccess software was used and time series were first checked and cleaned to remove obvious readout or transcription errors, including abnormal values, incorrect dating and logging absent values as zeros. Additional errors checks were based on the double mass method (Brunet-Moret, 1979), which rests upon the proportionality principle between data from two neighbouring rainfall gauges, to test the homogeneity of records from one gauge with those from a reference station (Kingumbi, 2006). Considering the dominant role of rainfall on runoff processes, an analysis of rainfall trends based on several statistical tests (Pettitt, Hubert segmentation, non parametric Mann-Kendall and Sen's slope) was undertaken (Pettitt, 1979; Hubert *et al.*, 1989; Yue *et al.*, 2002), using Khronostat (IRD, 1998) and MAKESENS (Salmi *et al.*, 2002) software.

Catchment runoff coefficients were studied at the annual and monthly time scale, and for 114 rainfall events over 15 mm. Events were defined as a period not exceeding two days during which runoff values do not return to baseflow level. Multi criteria analysis of the events relied on four parameters known to influence the catchment's hydrological response: rainfall volume and intensity, crop cover and antecedent soil moisture. Crop cover distinguished between bare and cropped soils based on the time of year, while soil moisture was assessed from the difference between rainfall over the preceding 20 days and potential evapotranspiration. Events over 15 mm were chosen due to reduced errors in the dam rating curve and their significant contribution to annual runoff (near 70%).

RESULTS

Influence of small reservoirs on catchment hydrological response

Monthly and annual runoff coefficients display a significant downward trend over the period 1996–2002 concurrent with the intense development of WSCW, which is not seen in R_C values for individual events over 15 mm (Fig. 1). This contradiction highlights the need to work at an event scale, considering the rainfall and runoff regime in the catchment, where 80% of the annual flow is produced over 12 days (Leduc *et al.*, 2007). Though highly variable, event R_C values do not display a marked and prolonged reduction in R_C over all events, which concurs with the hypothesis that WSCW have a moderate, second order impact (Lacombe *et al.*, 2008). Their influence must therefore be searched on minor variations of R_C for comparable events, and the marked reduction observed in monthly R_C values must be interpreted based on other parameters, notably rainfall and the observed reduction in the number of events over 15 mm.

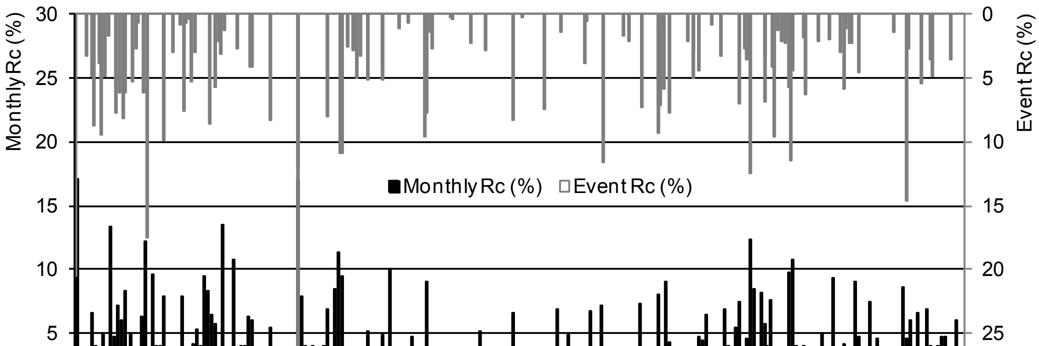

Fig. 1 Change in monthly R_C and R_C for rainfall events over 15 mm during the years 1989–2010.

Influence of small reservoirs on event R_C

On rainfall events under 40 mm, R_C values reduced by 40% after 1996, supporting findings from Lacombe *et al.* (2008) who identified a 55% reduction in R_C over 1997–2005. New data from the past 5 years indicate that mean R_C values have remained low, around 3.6% against 6.0% beforehand (1989–1996). To refine this analysis, changes in R_C over time for different sub-classes of events were compared. For summer events on bare soils, R_C reduced from 9.9% in 1989–1996 to 5.8% in 1996–2003, and continued to decrease to 4.0% over 2003–2010. For events on cropped, dry or low moisture soils, R_C also reduced from 4.2% to 1.4% before increasing slightly to 2.6% over the three same periods. Conversely, R_C for events on cropped wet soils, when the available capacity and influence of reservoirs may be reduced, remained relatively stationary.

On events over 40 mm, R_C values reduced by 20% over the period 2003–2010 compared to during 1989–1996 and 1996–2003. Nevertheless this result is not statistically robust, as the limited number of events in this category (31 over 21 years) prevented the analysis of a statistically significant number of events occurring in similar conditions (land cover, soil moisture, daily intensity) every year.

Table 1 Change in average R_C for rainfall events under 40 mm.

	1989–1996	1996–2003	2003–2010
Mean R_C	6.0%	3.6%	3.6%
R_C for events on bare soils	9.9%	5.8%	4.0%
R_C for events on cropped wet soils	4.0%	3.7%	3.4%
R_C for events on cropped dry or low moisture soils	4.2%	1.4%	2.6%
Number of events	35	21	27

Climate influence on catchment runoff

Relationship annual runoff–annual rainfall Analysis of annual rainfall trends over the period 1960–2011 did not identify any significant shift in the long term mean, capable of explaining the annual runoff deficit observed between 1996 and 2002. Time series revealed a high interannual variability, with mean rainfall around 329 mm/year and a coefficient of variation of 0.4, but the Buishand, Pettitt, Hubert, Mann Kendall & Sen tests confirmed with 99% confidence that time series follow a random distribution and exclude any long term downward trend. The same series of statistical tests was performed on the number of rainfall days and rainfall events over 20 mm/day and over 30 mm/day for time series from 20 individual gauges and interpolated across the catchment. No significant change was identified, in agreement with previous studies (Kingumbi, 2006; Slimani *et al.*, 2007).

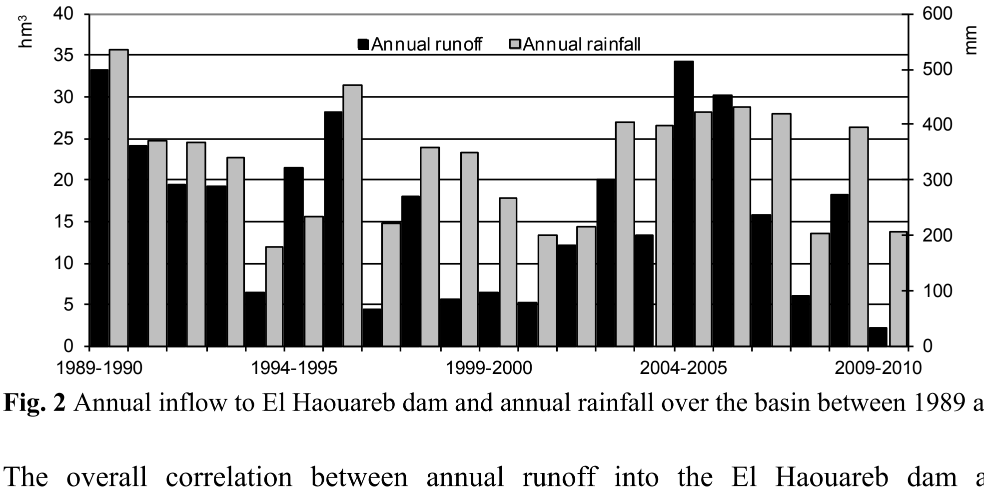

Fig. 2 Annual inflow to El Haouareb dam and annual rainfall over the basin between 1989 and 2010.

The overall correlation between annual runoff into the El Haouareb dam and annual catchment rainfall remains weak (Fig. 2, $R^2 = 0.66$) but a low correlation between these variables at this spatial and temporal scale is not surprising in semi-arid areas. This result is also coherent with former studies, which conclude that annual rainfall variations are not sufficient to explain the changes observed in downstream runoff (Kingumbi, 2006; Leduc *et al.*, 2007).

Relationship annual runoff–rainfall events Analysis of 114 events over the period 1989–2010 revealed that annual runoff is strongly correlated ($R^2 = 0.95$) with the runoff generated by rainfall events over 15 mm. The low number of these events (5.4/year) and the substantial contribution from a single event (up to 10 hm^3) to annual runoff reveal the need to understand in detail these events. Unlike annual rainfall, changes in the amount of rainfall events are seen to largely determine annual runoff (Fig. 3). Years where runoff exceeds the long term average, 7.1 events on average are witnessed, compared to only 3.6 during years of low runoff. Years when the correlation is not sufficient to explain runoff variations, differences in the conditions under which each event occurs must be accounted for (manuscript under preparation). In 1994–1995 for example, the three rainfall events over 15 mm took place on relatively bare soils, when soils were saturated from previous smaller events, and produced over 16 hm^3 runoff. Likewise, in February 2005 a single event of 100 mm produced 11 hm^3 runoff as it occurred on humid saturated soils, while a similar event of 85 mm occurred in December 2003 on cropped, dry soils produced only 3.8 hm^3. The spatial extent of these events was found to be comparable. The reduced runoff in 1996–2002 appears to have been caused by a reduced number of rainfall events and by larger events occurring during winters on poorly saturated soils, hence with naturally low R_C. The intensity of the summer events was also remarkably weak and generated very little runoff.

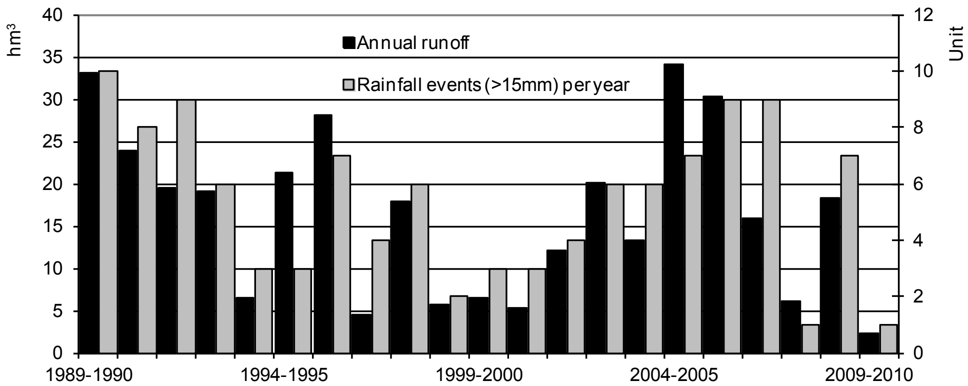

Fig. 3 Annual inflow to the El Haouareb dam and number of rainfall events over 15 mm per year (1989–2010).

CONCLUSIONS

Analysis revealed a 45% reduction in R_C over the period 1996–2010 on rainfall events under 40 mm on bare soils or cropped, poorly saturated soils. The reduction was observed for events of similar land cover and soil moisture, reducing ambiguity over their influence on the observed R_C variations. The absence of a reduction in R_C on saturated soils, when WSCW capacity may be reduced, also supports the hypothesis of an influence of WSCW during the other events. These events contribute around 60% to annual runoff, thus annual flows can be estimated to have reduced by 25–30% over the period of WSCW development in the catchment, where previous studies had assessed their influence as between 1 and 50%.

The major reduction observed over the period 1996–2002 concomitant to the development of small reservoirs and contour benches, was, however, shown to be largely related to the reduced number and the unfavourable conditions (low soil moisture, high crop cover) under which rainfall events over 15 mm occurred those years. Annual rainfall over 1989–2010 was weakly correlated with catchment runoff, but detailed analysis of 114 events revealed that annual runoff is closely linked to the inflow generated by a limited number of rainfall events over 15 mm (5.4/year on average). Variations in the number of these events, but also the circumstances under which they occur largely, determine the annual runoff in this semi-arid basin. Further analysis will be required to confirm that other factors, such as changes in land cover, hourly intensity of rains, spatial extent of rainfall events or baseflow were not responsible for the observed modification of the catchment's hydrological response. Reductions observed only in monthly and annual runoff coefficients highlighted the importance of focusing on individual events to account for the nature of rainfall in semi-arid areas.

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