Spatial redistribution of water resources in a Tunisian semi-arid catchment subject to conservation works

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ABSTRACT

In semi-arid areas, hydrological impact of water and soil conservation works (WSCW) has most often been studied at the local level. Studies at the regional scale are rare. In central Tunisia, the Merguellil catchment (1183 km^2) defined by the big El Haouareb dam has been subject to WSCW for several decades. They consist of contour ridges and small earth dams collecting hillslope runoff and wadi flow respectively. 97% of the surface areas equipped with WSCW between 1989 and 2005 are located in the lower area of the Merguellil catchment, downstream the Skhira upper subcatchment (189 km^2). In this lower area, 32% of the surface area is covered by WSCW. A regional and a local approach were developed. The first approach characterized the hydrological changes induced by WSCW at the Merguellil catchment scale. The space-time variability of the rainfall-runoff relationship was analysed, comparing the runoff responses of the Skhira upper subcatchment and of the lower subarea. Results indicate that between periods 1989-1996 and 1997-2005 the runoff produced by rainfall below 40 mm was reduced by over 70% in the lower area. This drop in runoff was estimated at about 45% when considering all rain depths and at about 30% when including the Skhira upper subcatchment in the analysis. Possible sources for the runoff reduction (climate, land cover, or water exchanges with the aquifer) were considered. The WSCW appear as the most likely cause. The second approach performed water budgets at the reservoir scale. In average, one third of the flow collected by earth dams is lost through evaporation and 11% are pumped for additional irrigation. In contour ridged hillslopes, the whole runoff collected in the ditches is probably evapotranspirated without any agricultural yield increase. The impact of WSCW on the water resources of the Merguellil catchment was assessed from the local and regional approaches. Expressed as percentage of total runoff produced in the catchment, infiltrated volumes and agricultural water uses changed from 54% to 40% and from 18% to 14% respectively. Evaporation changed from 27% to 41%. These changes are equivalent to a global 26% water resources decrease in the Merguellil catchment. It was proved that plantations of olive trees on the whole contour ridge areas would change this drastic water resources loss into a gain of up to 10%.

INTRODUCTION

In semi-arid and mountainous areas, erosion and droughts are recurrent problems that drastically reduce agricultural production. From the earliest times, local population have built water and soil conservation works (WSCW) in uplands to collect runoff and retain sediments. They generally consist of hillslope works (contour ridges) reducing surface runoff and increasing local infiltration and of small hillside earth dams collecting sediment-loaded headwater flows produced by intense rainfall. Stored water is generally used for supplemental irrigation of orchard trees during droughts and for market gardening. The hydrological impact of WSCW has most often been studied at the local level (Nasri, 2007; Nasri et al., 2004). With the fast growth of WSCW-equipped areas, it becomes necessary to investigate hydrological impacts and manage resources at larger scales. Although precise knowledge on the WSCW hydrological impacts is a prerequisite, it remains rare especially in large catchments (above 100 km^2) as heterogeneity and data scarcity increase with catchment size (Nandakumar and Mein, 1997). In semi-arid catchments, most hydrological impact studies have been conducted with respect to land use/land-cover modifications (Leduc et al., 2001), intensification of agricultural practices (Lorup et al., 1998) or to climate change (Séguis et al., 2004). The objective of this paper is to characterize the impact of WSCW on water resources availability in the Merguellil catchment, typical of semi-arid Tunisia where WSCW were introduced during the last decades. A regional and a local approach are developed. The hydrological changes induced by WSCW in the Merguellil catchment are first characterized. Then, water balances are performed at the reservoir scale. WSCW impacts on the water resources produced and stored in the Merguellil catchment are finally assessed from a spatial integration, using the local and regional approaches' results.

RESEARCH AREA

Wadi Merguellil is one of the three main temporary rivers reaching the Kairouan plain, in central Tunisia. The Merguellil catchment (1183 km^2) is defined by the big El Haouareb dam built in 1989 to protect the city of Kairouan against floods, about 60 km in the east (figure 1). The Merguellil catchment presents a hilly topography (altitude between 200 and 1200 m with a median of 500 m). About 70% of the catchment surface area has slopes below 7%. The mean annual rainfall (1929-2005) varies between 515 mm at the top of the catchment in the north-west and 265 mm at the catchment outlet. Monthly temperature varies between 10°C in February and 30°C in July. The mean annual pan evaporation (1989-2005) is 2075 mm. Four aquifers covering 600 km^2 are located in the downstream part of the catchment. Half of the catchment area is cultivated with annual crops (wheat, barley) and trees (olive and almond). Grazing lands cover 30%, forest 19%, and urban areas 1%. Downstream the El Haouareb dam, the Merguellil catchment is part of the Kairouan plain. Over 60% of the inflow collected by the El Haouareb dam infiltrates (Kingumbi et al., 2004). This dam is one of the main recharge points for the Kairouan plain aquifer (Leduc et al., 2007) which is the major water resource for this populated area. In the 1990's, the Tunisian government subsidized the construction of WSCW to reduce gully formation and allow supplemental irrigation in the Merguellil catchment.

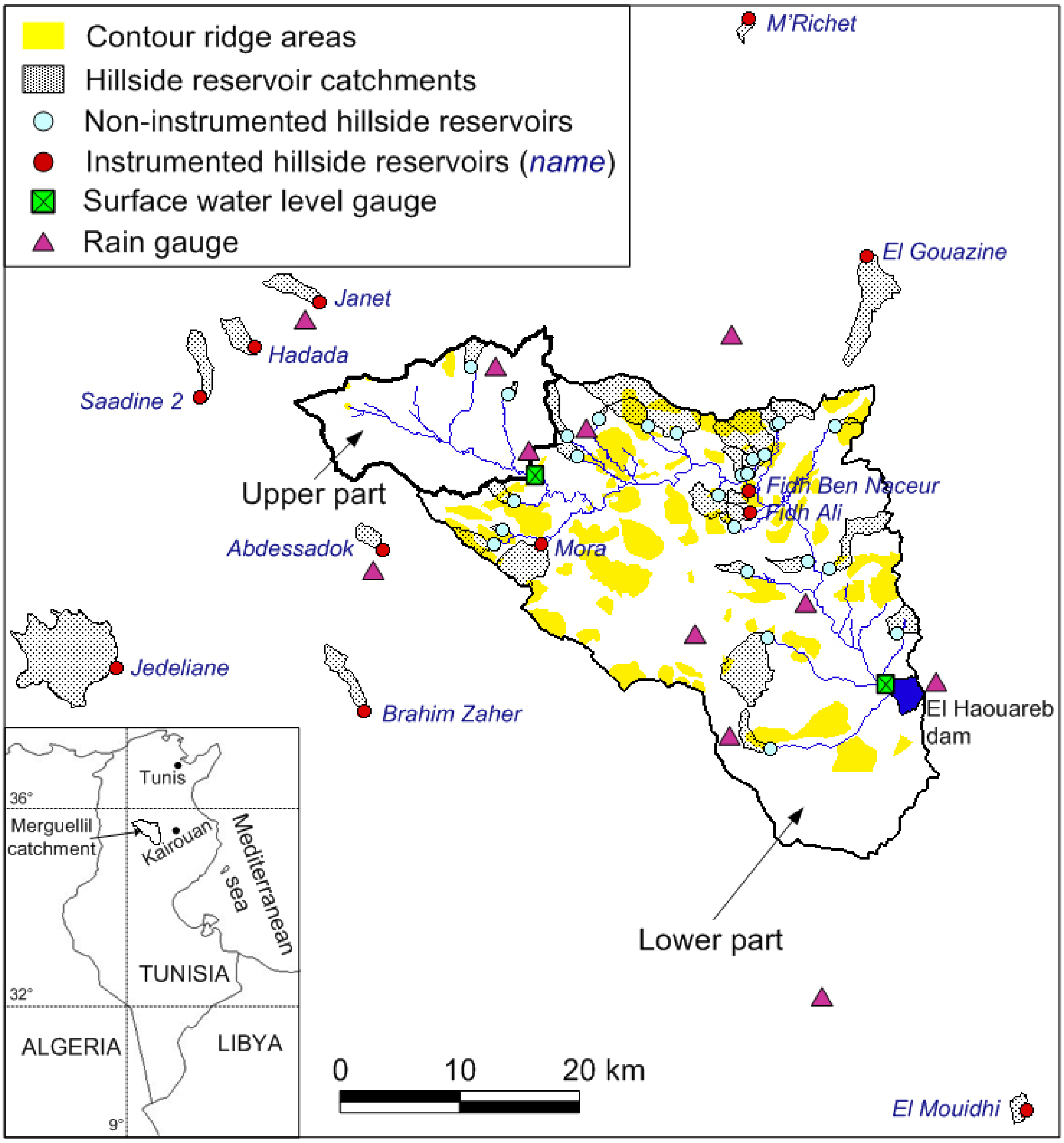

Figure 1. Water and Soil Conservation Works (1989-2005) and hydro-meteorological stations in the Merguellil catchment

MEASUREMENTS

Two water level gauges were used. Skhira station, located at the upper subcatchment outlet, has recorded instant discharge of the Merguellil wadi since 1974. The second gauge provides daily water level of the El Haouareb reservoir since 1989. Water balance calculations allowed estimation of daily inflows from the whole catchment. Dam releases are rare (3 days/year in average). Daily areal rainfall in the upper subcatchment and in the lower subarea was obtained by applying the Thiessen polygon method to 11 daily rain gauges providing data from 1981 to 2005 (figure 1).. The period for the rainfall-runoff analysis is 1989-2005, when all hydro-meteorological data are available.

Existing contour ridged areas were delimited on 2.5 and 10 m resolution SPOT images. Small dams were geo-referenced with a GPS. Contours of their catchments were drawn from 1:50 000 topographic maps. Between 1989 and 2005, 29 small dams were built, collecting runoff from about 130 km^2. Contour ridges were constructed over 230 km^2 of lands, 12% of which located within the catchments of the small dams. As of 2005, WSCW collect runoff from 28% of the Merguellil catchment surface area. 97% of WSCW-controlled areas are located outside the Merguellil headwater catchment defined by the Skhira gauging station (referred to as the upper part of the Merguellil catchment), in the downstream part of the Merguellil catchment where they control 32% of the surface area.

Twelve hillside dams in the Merguellil area are part of an environmental research observatory called Hydromed. In the mid of the 90', each of these reservoirs was instrumented with meteorological and hydrological equipments (figure 1). A tipping bucket type rain gauge enables to estimate the rainfall intensity over 5 min time steps. Pan evaporation is estimated with a Colorado - Orstom type tank. A water level gauge provides water levels in the reservoir with 1 cm accuracy. The spillway of the reservoir is shaped so that overflow is estimated from the observed water levels through a rating curve. Time series cover the period 1993-2000. The El Haouareb dam is equipped with a Colorado tank, a rain gauge and a water level gauge. Data have been collected every day since 1989.

DATA ANALYSIS AND RESULTS

Hydrological changes at the catchment scale

Figure 2 compares annual areal rainfall and runoff volumes for the upper part and for the whole Merguellil catchment. Most of the years, rainfall is about 17% higher in the upper part of the catchment. Until 1996, runoff collected at the Merguellil outlet is greater than this measured at the outlet of the upper part), in accordance with the spatial configuration of the two nested catchments. From 1997 to 2004, the difference between annual flows at these stations is considerably smaller. In 2005, flows differ significantly.

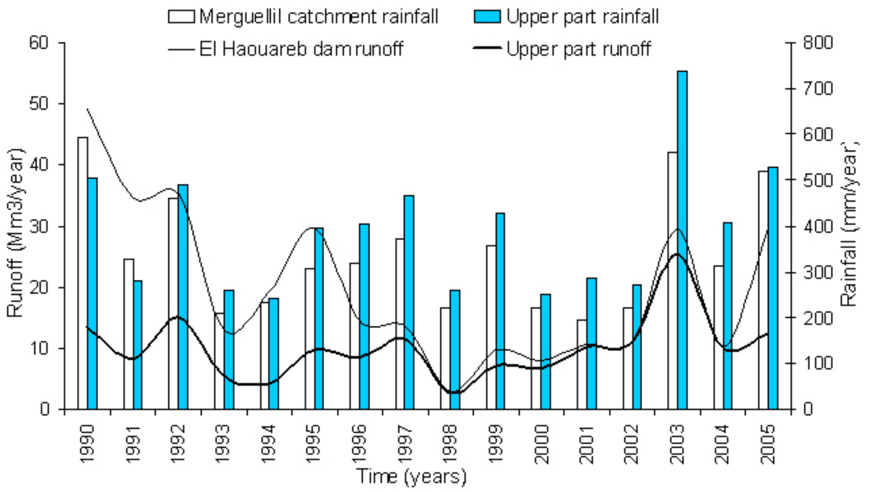

Figure 2. Yearly rainfall and runoff for Merguellil catchment and upper part (1990 to 2005).

Changes in water yields of the two Merguellil catchment parts and between periods 1989-1996 and 1997-2005 were analysed for different 10-mm rain depth classes, using a daily lumped rainfall-runoff model (Lacombe et al., 2008). This analysis indicated that runoff produced by rainfall below 40 mm was reduced by over 70% in the lower part between the two periods. This drop in runoff was estimated at about 45% when considering all rain depths and at about 30% when including the upper part in the analysis. No runoff change was found for rains above 40 mm in the lower part or for any rain depth range in the upper part (table 1).

Table 1. Mean water yield change coefficients [%] between periods 1989-1996 and 1997-2005

	Water Yield Change Coefficient		
	Merguellil catchment	Upper part	Lower part
Rain<40 mm	-55	4	-73
Rain>40 mm	1	2	2
All rains	-30	3	-45

Lacombe et al (2008) considered the possible causes for the runoff reduction (WSCW, climate, land cover, or water exchanges with the aquifer) and identified WSCW as the most likely cause. The time-averaged proportion of areas controlled by WSCW in the lower part changed from 5% to 26% between the periods 1989-1996 and 1997-2005, and from 2% to 5% in the upper part. This contrasted spatial distribution was seen as consistent with the contrast in runoff trend between the two areas (table 1). In this way, the 40 mm/event rainfall threshold may correspond to some mean effective storage capacity of the WSCW-equipped areas, averaged over the whole lower part. When this capacity becomes saturated, further rainfall produces wadi flow with a high runoff coefficient as if WSCW did not exist. At the catchment scale, the 30% runoff decrease is equivalent to a water resources deficit of about 6 Mm^3/year. This is a considerable loss for the irrigated Kairouan plain. Thus, it is necessary to investigate how the runoff collected by WSCW is used in order to assess the overall impact of WSCW on water resource availability at the catchment scale.

Reservoirs water balances

In this section, global water balances are performed for each type of WSCW and for the El Haouareb dam. It appears that the average dimensions (reservoir and catchment) of the 12 equipped hillside dams and of the 29 hillside dams inside the Merguellil catchment are similar. Therefore, the global water balance of the 12 equipped dams is used to estimate that of the 29 reservoirs of the Merguellil catchment. The reservoirs water balances (hillside and El Haouareb dams) are defined by the general hydrological equation based on a statement of the law of conservation of mass (figure 3). The reservoir inflow components are surface and subsurface runoff (R) and precipitations on the reservoir (Pr). The reservoir outflow components are evaporation (E_{RES}), infiltration (I), pumping for agricultural use (Pu), spillway outflows (O) and dam releases for artificial groundwater recharge or for silt removal (D). At each time step, the difference between the reservoir inflows and outflows results in a change in storage (ΔV). The equation is expressed as follow: $\Delta V = R + Pr - [E_{RES} + I + Pu + D + O]$.

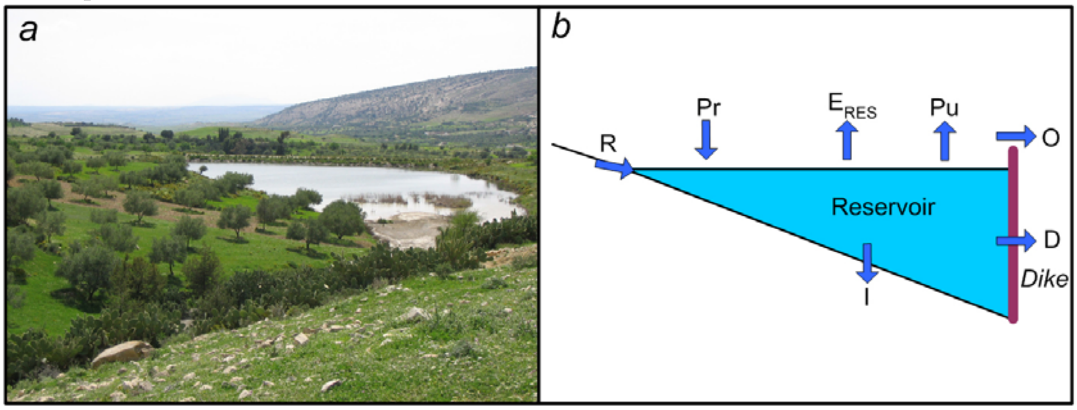

Figure 3. a/ One of 29 hillside dams built in Merguellil catchment over period 1989-2005. b/ Water balance components. Refer to last paragraph for legend.

ΔV, Pr and O are directly estimated from measures. Other terms of the water balance equation are estimated in three steps, each of them corresponding to a specific situation.

1. First of all, the equation is solved for inflow periods. Because of sparse vegetation, low water holding soils and pronounced topography, river flows react rapidly to rainfall. Flood hydrographs are sharp and short. During these episodes, except for spillway outflows and precipitations, other terms of the equation are negligible. The general equation of the reservoir water balance simplifies and R is estimated as follow: $R = \Delta V - Pr + O$.

2. The reservoir evaporation (E_{RES}) and the infiltration (I) are estimated on periods without inflow (R=0 and O=0), pumping (Pu=0) and dam release (D=0). In this case, the general equation of the reservoir water balance becomes: $-\Delta V = E_{RES} + I$. This equation is solved at the daily time step. Considering that the daily variations of the reservoir's surface are trivial, the equation is written as follow: $-\Delta L = K_{PAN} \times E_{PAN} + D \times L$ where all components are expressed in mm/day. ΔL represents the water level variations in the reservoir. E_{PAN} is the pan evaporation and K_{PAN} is a pan coefficient. D is the drainage coefficient and L is the water level in the reservoir. D and K_{PAN} are estimated from multiple linear regressions. Results are of good quality for 9 out of the 12 hillside dams ($69\%<R^2<90\%$). The model can neither be applied to the El Haouareb dam nor to the 3 hillside dams Brahim Zaher, El Gouazine and Fidh Ali. The natural emptying of the El Haouareb dam depends on the water table level (Kingumbi et al.,2004) and cannot be modelled by our linear model. In the case of the 3 hillside dams, infiltration intensity was found to be constant regardless of the water level.

3. Pumping and dam release volumes were determined during dry periods using the simplified water balance equation: $Pu + D = -[E_{RES} + I + \Delta V]$. Pumping and dam releases never occur simultaneously and released volumes are greater than pumped volume. Therefore, Pu and D were individually estimated, using a specific threshold determined for each reservoir. This method was verified and validated using data from the El Haouareb dam which is the only reservoir whose releases and pumping have been monitored since its building (Lacombe, 2007).

Figure 4 (A) shows the water balances of the reservoirs (El Haouareb and hillside dams), calculated from time series covering the period Sept. 95 – Aug. 99, when all data are available. For the El Haouareb dam, the K_{PAN} coefficient was set to the mean value of 0.9 and infiltration was then deduced from the equation: $-\Delta L = K_{PAN} \times E_{PAN} + I$. Hillside reservoirs are much less exploited for irrigation (pumping=11%) than the El Haouareb dam (pumping=18%) whereas dam releases are more frequently operated from the hillside reservoirs.

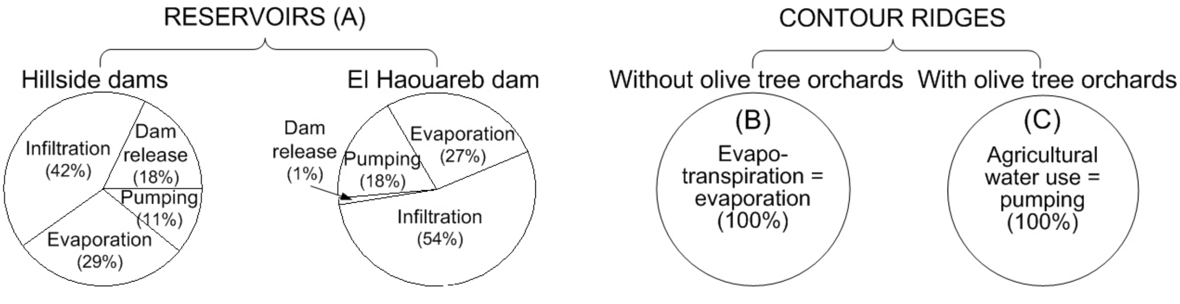

Figure 4. Water balances of WSCW and El Haouareb dam

Little information is available to describe the contour ridges' water balance. Therefore, it is estimated from simple assumptions: due to the high evaporation demand and to the depth of the water table surface in contour ridges areas, it was assumed that after a rainfall, the soil is finally drought up through capillary rise and evapotranspiration so that percolations from the ditches never reaches the water table. After having been collected in the contour ridges' ditches, runoff infiltrates in the soil and is an available water resource for the crops. Roose (2002) found that olive tree is the best suited crop to benefit from this additional water, thanks to its deep root zone and its submersion tolerance. Unfortunately, most of the contour ridges were built on bare soils or in cereal fields. In that case, the possible gain in cereal production is compensated by a loss of arable lands due to the embankments. Two opposite situations are considered in figure 4. In figure 4 (B), all contour ridges are unplanted. This explains why 100% of the collected runoff is finally lost through evapotranspiration without any agricultural yield increase. In the second case, figure 4 (C), all contour ridges were suitably planted with olive trees. The water collected in the ditches is used by the trees as if it had been provided through irrigation from the hillside dams. The real situation must correspond to an intermediate situation between (B) and (C).

Spatial integration

Figure 5 describes the method used to investigate the impacts of the WSCW on the water availability in the Merguellil catchment. The balance of water stored in the catchment is assessed before and after the introduction of WSCW. In the first situation (corresponding to the hydrologic period 1989-1996, cf. figure 2), it is assumed that the whole catchment runoff is collected by the El Haouareb dam. In that condition, the water balances of the catchment is equivalent to that of the El Haouareb dam.

In the second situation (the catchment is equipped with WSCW; this period corresponds to the hydrologic period 1997-2005), the overall water balance of the catchment is assessed from the WSCW' and the Haouareb dam's water balances. During this second period, about 30% of the runoff produced in the Merguellil catchment is collected by WSCW (table 1). Lacombe (2007) found that 5% (resp. 25%) of runoff that would have filled the El Haouareb dam during the first period are collected by the hillside dams (resp. the contour ridges) during the second period. Once runoff is collected by WSCW or by the El Haouareb dam, it is subject to the water balances described in figure 4. In figure 5 (A), contour ridges are not planted with olive trees and the whole runoff they collect is evapotranspired without any agricultural yield increase (i.e. evaporated). In figure 5 (B), contour ridges are covered by olive tree orchards so that collected water in the ditches is used by the olive trees as if it would have been provided by irrigation. In both cases, the overall water balance of the Merguellil catchment is obtained by summing the WSCW and the El Haouareb dam's water balances, after having weighted them by the proportion of the Merguellil catchment's runoff they collect. WSCW impact on water resources availability is assessed by comparing the overall water balances of the two periods 1989-1996 and 1997-2005. In case (A), expressed as percentage of total runoff produced in the catchment, infiltrated and pumped volumes changed from 54% to 40% and from 18% to 13% respectively. Evaporation changed from 27% to 46%. Considering that infiltration and pumping preserve the water resources whereas evaporation is a loss, these changes are equivalent to a global 26% water resources decrease in the Merguellil catchment. In case (B), WSCW and olive tree plantations on contour ridges induce a global 10% water resources increase.

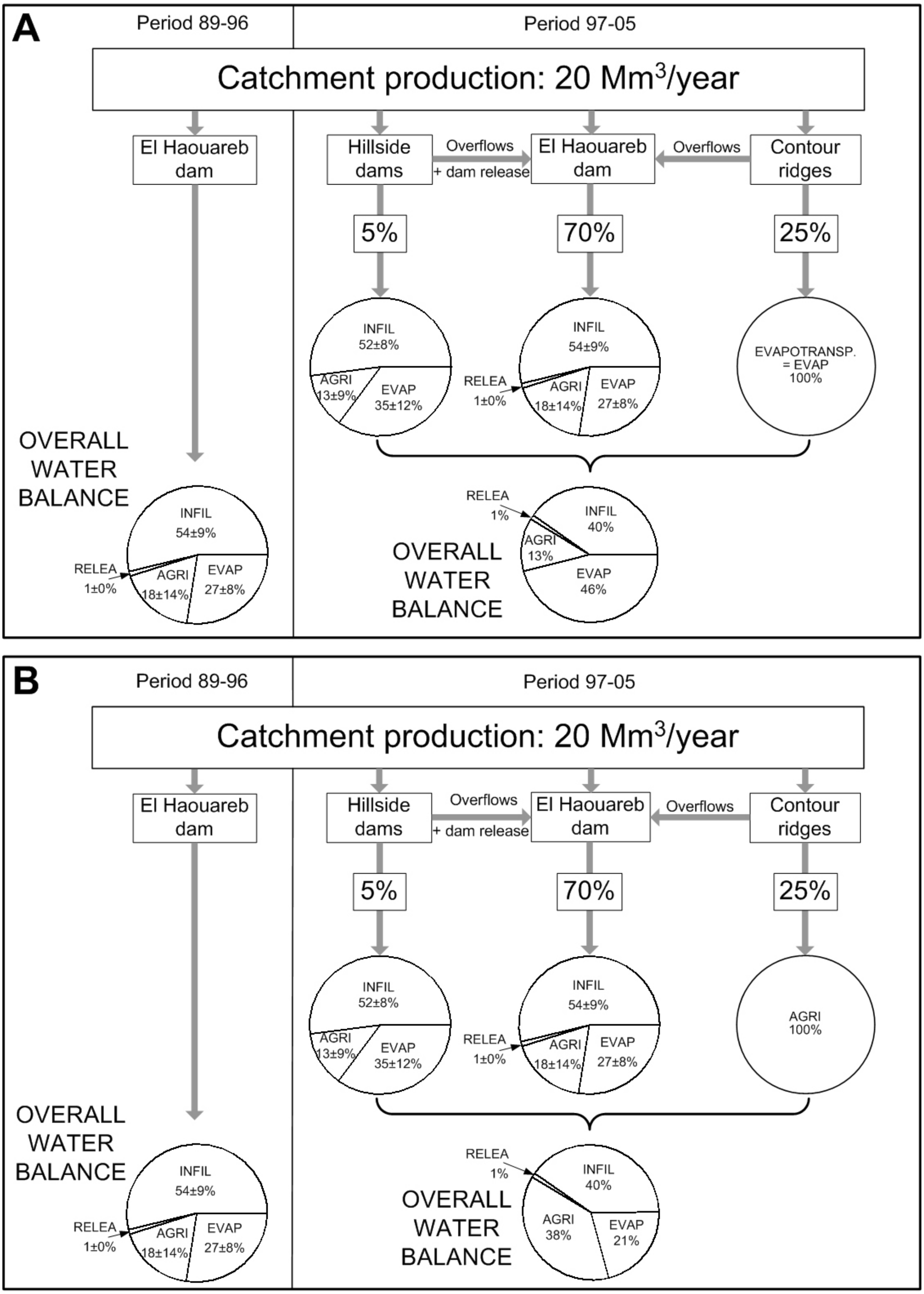

Figure 5. WSCW impact on water resources availability in Merguellil catchment. A: Contour ridges are either unplanted (A) or covered by olive tree orchards (B). EVAP: evaporation, EVAPOTRANSP: evapotranspiration, INFIL: infiltration, RELEA: dam release, AGRI: agricultural water use.

DISCUSSION AND CONLUSION

At the catchment level

Several research works have been conducted to estimate the hydrological impact of WSCW in the Merguellil catchment. It is interesting to observe the diversity of results, sometimes contradictory. Dridi (2000) found that the reduction coefficient of runoff in the Merguellil catchment was equal to the proportion of the WSCW-equipped areas. On the other hand, Kingumbi (2006) maintained that WSCW had a limited impact (1% decrease runoff) and that the runoff reduction was mainly explained by a reduction of low flows resulting from the water table drawdown. Although we are confident in the results we obtained with our own method, the diversity of these three studies' conclusions underline the difficulty to clearly identify the hydrological impact of WSCW in a changing and unsteady environment (extreme rainfall variability, increase of pumping in the water table, land cover changes). Further investigations should be conducted to differentiate the impacts of changes in surface conditions from the underground's once.

At the conservation works scale

Reservoirs water balances have been calculated over a 4-year period (Sept. 95 – Aug. 99). Due to the extreme inter-annual rainfall variability in this semiarid region, such a short period is not representative of the climate fluctuations which may influence the different terms of the water balance. During dry years, the dams contain less water and the predominant components of the water balance are evaporation and pumping. During humid years, the main outflows components are spillways outflows, infiltration and dam releases. Nevertheless, it was shown that the overall hillside dams' water balance estimated from the 1995-1999 time series was similar (less than 1% differences for each term) to that obtain from all available hydrological time series over the period 1993-2000. In contour ridged areas, further studies should investigate the aquifer recharge mechanisms to identify a possible influence of contour ridges.

About spatial management of water resources

This research has demonstrated how efforts in water and soil conservation have finally led to moderate successes: as things are, because of high evaporation losses, WSCW have induced a water resources decrease of about 25% at the catchment scale. This decrease could be changed into a water resource gain of 10% provided that all contour ridge areas are planted with olive trees. This proves that WSCW are not an overall solution to all water scarcity problems. When WSCW are installed upstream a pre-existing dam (the El Haouareb dam in our case), it is crucial to compare the water balances of the different equipments. When water resources preservation is the main objective, WSCW are beneficial at the condition that they induce less evaporation losses than the downstream dam. This result should encourage the decision-makers to consider the topologic relations between water works.

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