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Ecohydrology and groundwater resources management under global change: A pilot study in the pre-Saharan basins of southern Morocco

Mohammed Messouli, Abdelkrim Ben Salem, Bahia Ghallabi, Mohammed Yacoubi-Khebiza, Ali Ait Boughrous, Asmae El Alami El Filali, Saloua Rochdane and Fatima Ezzahra Hammadi

Department of Biology, LHEA-ESSI, FS Semlalia, Marrakech, Morocco

Abstract. The Tafilalt Oasis, which is part of the UNESCO Biosphere Reserve, is located in the pre-Saharan region of Morocco. Due to the arid conditions of this area, the local population, infrastructure and livestock farming are concentrated around the rivers and the oases. The ephemeral river flows force the population to use groundwater (GW) in order to meet water needs. Consequently, GW proves to be of utmost importance for water management. The Driving force-Pressure-State-Impact-Response (DPSIR) framework was applied to ensure a proper relationship between policies, economic issues and the most important GW development and management issues. The aim of this paper is to review the Water Evaluation and Planning (WEAP) model and its application to the Ziz basin. This model allows to simulate and analyse various water allocation scenarios and, above all, a number of scenarios concerning the users' behaviour. Water demand management is one of the options discussed in more detail. There is ample evidence of degradation, pollution and overexploitation of water resources, resulting from inappropriate groundwater management systems based on the administrative division. But it is possible to achieve sustainability in groundwater use by integrating the hydrological and ecological approaches. The ecohydrological method, based on profound understanding of the complexity of the ecosystem processes at different levels, provides new opportunities for groundwater resources protection compared with traditional, exclusively technologically-oriented methods

Keywords. Ecohydrology – Oasis – Sahara – Climate change – Adaptation – Management.

Éco hydrologie et gestion des ressources en eau souterraines dans le cadre d'un changement global : une étude pilote dans les bassins hydrographiques présahariens du sud du Maroc

Résumé. *Les oasis de Tafilalet, qui font partie des Réserves de Biosphère de l'UNESCO, se trouvent dans la région présaharienne du Maroc. Vu les conditions arides de cette région, la population locale, les infrastructures et l'élevage sont concentrés autour des rivières et des oasis. Les flux éphémères des rivières obligent la population à exploiter les eaux de nappe afin de satisfaire leurs besoins. Par conséquent, les nappes jouent un rôle primordial pour la gestion de l'eau. Le modèle DPSIR (Driving force-Pressure-State-Impact-Response) a été appliqué pour établir la relation correcte entre les politiques, les problématiques économiques et celles relatives au développement et à la gestion des eaux de nappes. L'objectif de ce travail est de passer en revue le modèle d'Evaluation et Planification de l'Eau (WEAP) est ses applications au bassin de Ziz. Ce modèle permet de simuler et d'analyser les différents scénarios de distribution des ressources en eau par rapport au comportement des usagers. La gestion de la demande d'eau est l'une des options illustrées en détail. De nombreux facteurs contribuent à confirmer que la dégradation, la pollution et la surexploitation des ressources en eaux représentent un problème important, causé par une gestion inappropriée de la nappe basée sur la division administrative. Cependant, il est possible d'assurer une utilisation durable des eaux de nappe, en intégrant les approches hydrologiques et écologiques. La méthode écohydrologique, qui évalue d'une manière approfondie les processus complexes de l'écosystème à différents niveaux, offre de nouvelles opportunités pour la préservation des eaux souterraines par rapport aux méthodes traditionnelles, exclusivement orientées aux applications technologiques.*

Mots-clés. *Ecohydrologie – Oasis – Sahara – Changement climatique – Adaptation – Gestion.*

I – Introduction

In most oases the Moroccan groundwater systems are submitted to drastic changes due to both global scale stresses and the cumulative effects of local and regional scale impacts. GW adaptive capacity and resilience are severely affected by the high drivers‘ magnitude. The Tafilalt Oasis is located in the pre-Saharan region of southereastern Morocco (Fig 1), covering an area of about 1,370 km^2, Ramsar site no. 1483, which is part of the UNESCO Biosphere Reserve, a site of Biological and Ecological Interest. This site comprises a series of oases and the reservoir of one of the oldest dams in Morocco (Hassan Dakhil). Some important atmospheric events occur in the region, such as sand invasion. The environment degradation, caused by deforestation and over-harvesting, has become a matter of great concern, because floods and drought are increasingly reported. Irrigation in the oases mostly depends on a dense and intricate network of canals distributed across the oasis. In the northern part of the Tafilalt oasis, since the late-14th century, water for irrigation canals has also been supplied by khettara (subterranean channels draining perched water table). Starting from the early 1970s, the remaining active khettaras have showed a reduced flow, and over the next two decades many more khettaras have dried up and have been abandoned. The reduction and abandonment of khettaras can be attributed to the Hassan Adakhil dam and its new reservoir upstream of Tafilalt oasis. Due to the dam’s control of downstream water release, many river channels downstream only have water during certain times of the year, a phenomenon which is worsened by excessive water abstraction for agriculture and human consumption and drought, that has become more frequent during the past two decades. Farmers are adopting too slowly proper techniques and equipment to save irrigation water. The low-cost boring technology and the cheaper imported and locally produced pumps have enhanced GW mining in Tafilalt. Pumps have had a decisive role in green revolution and poverty alleviation but the present development of uncontrolled GW markets is posing a threat to the sustainable use of GW reserves.

The downstream reservoir, Hassan Dakhil, located near Errachidia, the regional capital city, strongly depends on water input from the mountain catchments. Over the past few years, there have been large fluctuations of water input into the reservoir and often, its minimum capacity is not reached. Apart from being negatively affected by several years of water shortage, the Hassan Dakhil dam has also been subject to substantial infill by sediments and consequently, to a rapid capacity loss.

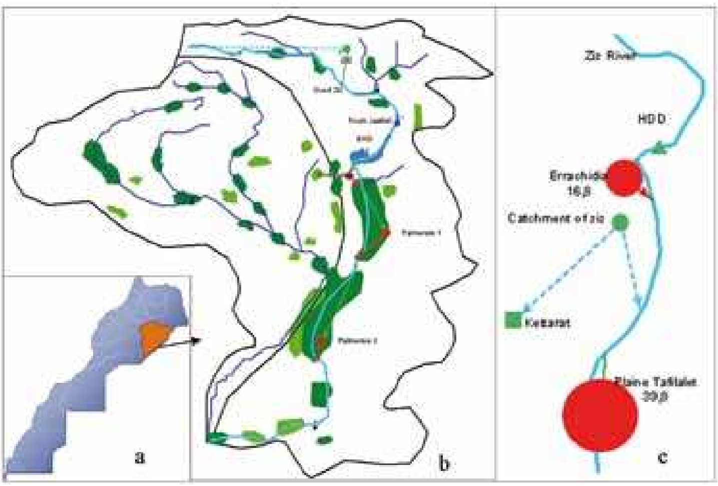

Figure 1. a) Ziz basin in Morocco b) schematic representation of the Ziz basin for the WEAP analysis c) scheme detail.

The climate is continental and arid. Rainfall ranges from 70 mm in the extreme South, at Erfoud, to 290 mm in the extreme North, at Imichil. These climatic conditions inhibit rainfed agriculture and make the use of irrigation necessary .

This paper outlines the rationale for a new approach to integrated water resources management from the local farm scale to the watershed and basin scale, which incorporates the proper balance of green and blue water flows in agriculture and freshwater to sustain the ecosystems and the downstream water use for human consumption.

II – Methods

The Driving force-Pressure-State-Impact-Response (DPSIR) framework was applied to ensure the proper relationship between policies and economic issues and the most important water development and management issues*.* Land-use scenarios for qualitative and quantitative analysis were designed and formulated in detail to face specific problems. The following aspects were taken into account: climate change, population dynamics, socio-cultural change, institutional change, economic development, and technological innovation.

The Upper Ziz hydrology was represented by the WEAP (Water Evaluation and Planning System) model (SEI, 2005). The model was adapted, calibrated and validated for the Ziz Basin in the framework of MIOS (Modèle Intégré des Oasis du Sud) and allowed the analysis of different hydrological parameters in different climate and policy scenarios. With WEAP, the first Current Account of the water system under study was created. Then, based on a number of demographic, hydrological, and technological trends, a “reference” scenario projection was elaborated, referred to as the Reference Scenario. Furthermore, one or more policy scenarios were developed with alternative assumptions about future developments.

Only the major water users were described along with the activity level, the annual water demand (net values after loss account), the monthly variation as well as the return flow.

Growth rates between 1993 and 2030 were estimated as follows: domestic 1.12-1.2%, livestock 1.2%, and irrigation 1.2%. (IRATE, 2006).

The work was based on detailed information including ecological, meteorological, hydrological, hydroeological, sedimentological, water management, GIS and remote sensing, vegetation, social, cultural and economic data (Ait Boughrous, 2007; Cappy *et a*l. 2004; De Jong *et al*., 2004; Ilahiane, 2004; Knippertz *et al*., 2003a,b ; Messouli *et al*., in press; Zeroual, 1995).

III – Results and discussion

In Moroccan oases many driving forces (Table 1) are leading to irreversible changes in the subsurface environment. The trend is the subsurface being increasingly used for different functions. In particular, in densely populated areas, along the Ziz and Draa Rivers, these functions may be in conflict with each other. These functions go beyond water demand for different proposes and also need physical space in the subsurface. These multiple uses of the subsurface according to the functions will lead to extend more the physical planning policies to the subsurface.

The reference scenario is the basic scenario that includes the actual data to gain knowledge about the period under study. The aim of a reference scenario is to help the planner and the water resources manager understand what can likely occur if the current trend continues, and the current status of affairs. Reference scenarios can also be useful to identify the weaknesses of knowledge and if more information needs to be collected. They can help design contingency plans where risk and uncertainty level is high.

Table 1. The major global threats to the surface/ groundwater systems in the Oases and the related issues (modified from Meybeck, 1998 and Meybeck, 2003). The scope and intersections of the several forcing and system impacts require an interdisciplinary and systematic research approach. A: human health, B: water cycle, C: water quality, D: carbon balance, E: fluvial morphology, F: aquatic biodiversity. Only the major links between issues and impacts are listed

Environmental state change	**Major impacts**	**Global issues**					
		A	B	C	D	E	F
climate change	Change in flow regime (recharge, runoff volume and timing)		■	■		■	
	Change in wetland distribution	■	■	■	■		■
	Change in erosion and sedimentation				■	■	
	Chang in chemical watering				■		
	Accelerated salinisation through evaporation	■	■				■
	Development in non-perennial rivers and desertification		■	■	■	■	■
Water management (including dams, diversions, khettaras and channelization)	Nutrient and carbon retention				■		
	Particulate retention				■	■	
	Change in flow regime (runoff volume and timing)		■	■		■	
	Stream flow variability and extremes		■				
	Loss of connectivity (L, V and H) *						■
Land-use change	Wetland filling or draining		■	■	■		■
	Change in sediment transport				■	■	
	Change in vegetation cover		■				
	Alteration of first order streams					■	■
	Nitrate and phosphate increase	■		■	■		
	Pesticide increase	■		■			
Irrigation & water transfer	Change in flow regime (runoff volume and timing)		■	■			■
	Salinisation through evaporation		■	■			
Release of domestic wastes (latrines, manners)	Heavy metal increase	■		■			
	Eutrophication	■		■	■		■
	Development of water diseases	■					
	Organic pollution	■		■			■
	Persistent organic pollutants	■	■	■			

(L, V and H)* = Lateral, Vertical and Horizontal

Due to evapotranspiration, water in the catchments will not totally run off to the rivers. WEAP uses the rainfall runoff method (FAO) to calculate the ratio between the crop demand and the runoff to the river. The Rainfall Runoff Method applies the crop coefficients to calculate the potential evapotranspiration in the catchment, then it determines any irrigation demand that may be recorded to face the amount of evapotranspiration requirement that cannot be met by rainfall.

The remaining rainfall not consumed by evapotranspiration is simulated as runoff to a river, or it can be proportioned considering the runoff to a river and the flow to groundwater via catchment links (SEI, 2005a).

Figure 2 shows the inflows and outflows of the main reservoir in Ziz basin. The graph is a balance between inflow and outflow. This graph is very useful to understand the operation of the reservoir throughout the year. The outflow from the reservoir is recorded in the summer time, when there is no rainfall and the “lachers” are necessary. The “lachers” bring about the storage volume decrease in the reservoir. Approximately 25% of the reservoir volume is lost by evaporation. At present, some problems of evaporation estimation and modelling are still unsolved and as a result, measures aimed at reducing evaporation from the lake reservoir surface are under discussion. The reservoir maximum capacity is used yearly, but with declining refill levels no water storage is possible on an annual basis. The combined effects of water planning for the lachers and of drier conditions compared with the annual average have resulted in a large drop in average water allocation for the irrigated date palm groves since the 1980s. During very dry years the lachers are not used for crop irrigation and are instead exploited to replenish GW levels.

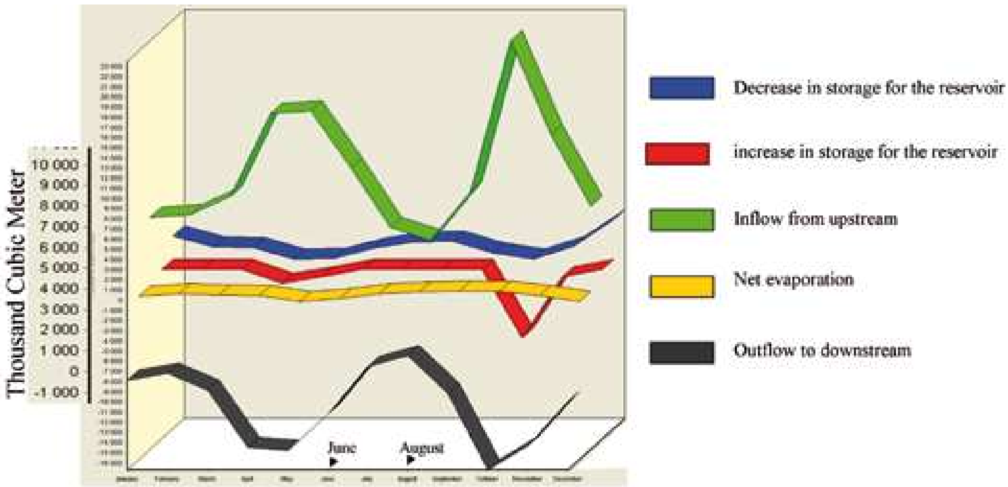

Figure 2. Monthly Ziz inflows and outflows (average 1976-2007).

1. Soil degradation and colmation

Water-induced soil erosion is a severe problem in the Ziz Basin region as demonstrated by the analysis of sedimentation in the reservoir Hassan Dakhil, located in the middle of the catchment. If the rapid dam infill due to high sediment transport into the rivers continues at the present rate, the dam will no longer be fully operational for irrigation by the year 2030. Even now, the dam capacity is insufficient to meet the needs of the downstream consumers during drought and in water-shortage conditions. Once the dam reaches a critical silted level (at about half its capacity), it will loose its regulatory flow. Irrigation will increasingly be subject to irregular, flood-dominated flows and will rely more heavily on groundwater resources. As a result, evaporation will show a decrease in the climate scenarios (figure 3).

In the future, the extensive spread of the oasis area at the outlet of the mountain areas must be controlled, since extensive water withdrawal in these higher regions can strongly affect the amount of water left for irrigation from the dam.

Increase in sediment colmation and in clogging intensity is currently observed, related to human activities. This may alter the hydrological and biological exchange through the hyporheic zone and, more specifically, modify the ability of the hyporheic interstice to provide a refugial area to benthic invertebrates. Moreover, the aquifer recharge can be interrupted (Messouli *et al*. in press). Xerophytes are widely exploited as a source of domestic energy near the grouped or scattered houses, thus contributing to the expansion of desertification. Livestock farming is dominated by goats and sheep which have increased along with the population. The resulting increase in grazing pressure has caused a decrease in the vegetation density and some changes have occurred in the vegetation diversity in both the lowlands and the highlands.

In general, groundwater storage declines across all the scenarios (not illustrated), except for downstream of the dam where the recharge will increase following the rapid dam infill. However, the decline rate is variable. As expected, for Water in the Environment scenario, the imposed restrictions for groundwater withdrawal limit the storage decline in the 2025 scenario. The effects of land use change and climate change on storage are also clearcut. More groundwater is extracted under the combined land use and climate change scenario because of increased evaporative demand for agriculture. Furthermore, under the Water for Food scenario, the current withdrawal rates are not sustainable. These findings can be generalized across the individual groundwater sub-basins, although the depletion severity varies widely.

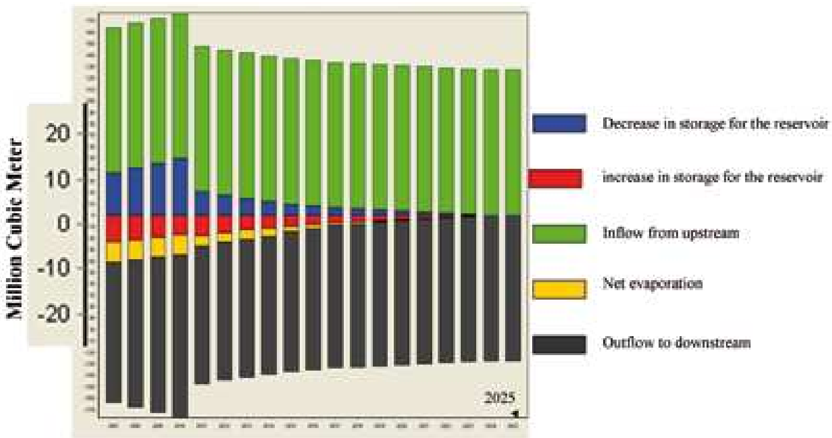

Figure 3. Yearly inflows and outflows simulated with WEAP for the 2025 scenarios in the Ziz basin.

The simulation results shown in figure 4 demonstrate that the average annual unmet demand will dramatically increase up to 70% and 90% of the total annual demand, respectively for January and July. For Errachidia, which lies in the middle of the basin, the simulation with WEAP suggests that the requirements for July will be hardly met in normal years. This is probably due to their position in the basin, and consequently, investigation should be furthered. On the other hand, in other locations, limited efforts appear to be sufficient to meet the local requirements.

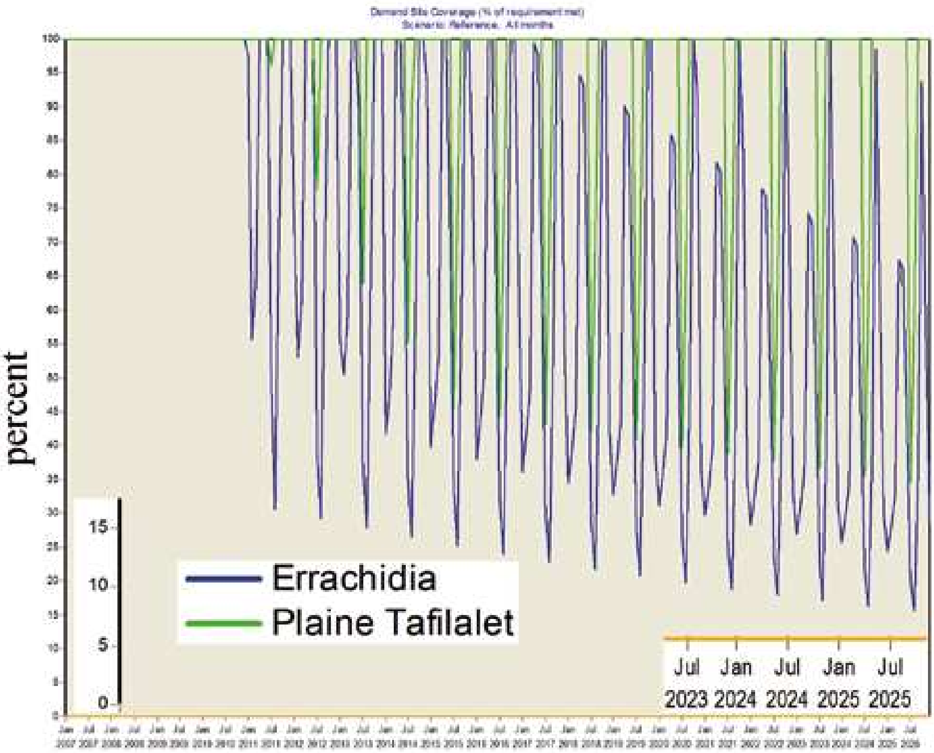

Figure 4. January and July water demand coverage (%) for each year simulated with WEAP for the 2025 scenarios in the Ziz basin.

It has been underlined that many users have developed their own strategies to cope with water shortage: for instance, using boreholes or developing their own storage systems (Matfia). These “shortages” sometimes represent half of the demand. But in general, they are quite limited (e.g. 20% in the case of irrigation schemes). Therefore it is necessary to accurately validate these results through further field surveys in order to ascertain the possible effects of data uncertainty and the extent to which water-users adopt alternative strategies, applying ecohydrology

Ecohydrology is more than just hydrology and ecology combined. It is fully functional only if science, engineering and construction, public administration and political decision assist each other in an integrated scheme and on a common scale. The Biosphere Reserve “Tafilalt Oasis”, in southern Morocco, depends on all the four aspects to be sustained.

The results of the first phase of the work implementation show the potential for the application of ecohydrological and phytotechnological measures in the Ziz Basin, which have raised the interest of local and regional authorities. The integrated approach to Ziz catchment and river-reservoir management has to address several aspects. Hydropower generation requires stabilisation of the hydrological cycle in the catchment by setting spatial planning and land-use regulations. Improving water quality requires several parallel actions, including wastewater technology for sewage treatment and ecohydrological methods. Based on ecohydrology, a simplified model of sustainable groundwater management can be developed (figure 5).

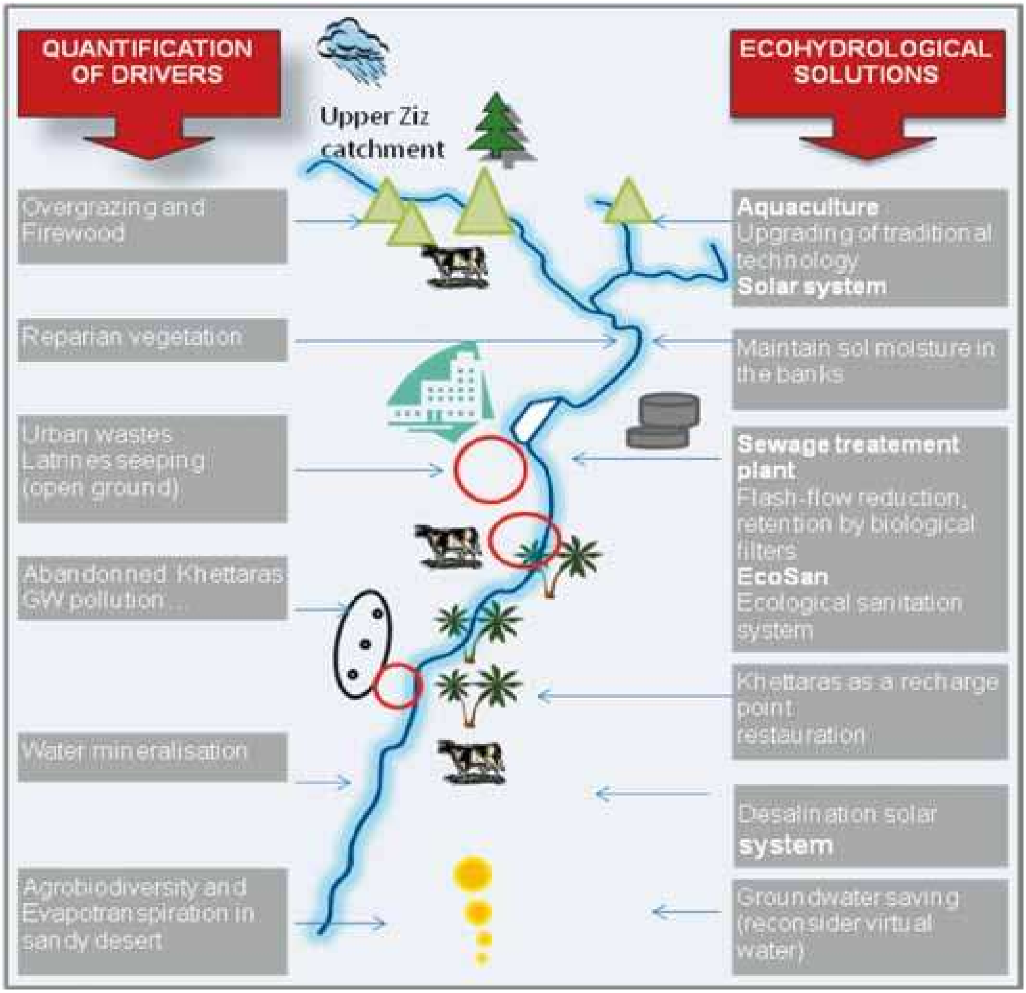

Figure 5. Application of ecohydrology: ranked impacts and adaptation.

The integrated approach to catchment and river-reservoir management has to address several aspects. Hydropower generation requires stabilisation of the hydrological cycle in the catchment by setting spatial planning and land-use regulations. Improving water quality requires several parallel actions, including wastewater technology for sewage treatment and ecohydrological methods. Hydraulic modelling will enhance sedimentation in controlled areas at the river mouth. The removal of sediments, which can be used as fertilizers by the local farmers, will reduce internal nutrient loading. Special attention shall be given to increasing environmental awareness in local communities. This will entail the enhancement of traditional aquaculture technologies, the reduction of environmental degradation (e.g., ecotone vegetation zone degradation,) and new economic opportunities (e.g., new farming opportunities).

IV – Conclusion

This study represents a first attempt at applying and testing the WEAP model as a means to address water allocation issues in a water-stressed river basin in Moroccan oases.

Groundwater will continue to be used intensively and the spread of irrigated agriculture will likely develop new groundwater sources, particularly as the markets for agricultural produce change. This process will be accompanied by land exclusion from irrigated production caused by physical depletion, migration of low-quality water, economic depletion (where pumping costs become excessive), waterlogging and salinisation, and groundwater use outside agriculture. The ecological impact on some ecosystems seems strong and probably irreversible. As a result, it is appropriate to be very cautious when simulating the hydrological impacts of CC or when analyzing runoff trends. Land-use change may have serious effects on hydrological processes; so far they have been more significant than any perceived or predicted CC impacts. It is necessary to take them into account explicitly by using, for instance, an appropriate hydrological model. In any case, CC impacts have to be separated from land-use impacts. The on-going PhD study (by Ben Salem) is improving the scenarios developed and the weaknesses of the current methodology. Therefore the following results may be envisaged: a) a better-performing simulation of the dam operating rules and of the restriction impact during drought, b) the assessment of the social and economic consequences of the different scenarios, c) the evaluation of the impact of further groundwater resources (i.e. conventional aquifers and dewatering of abandoned khettaras) development and use, and d) the evaluation of the possible impact of climate change.

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