Dryland hydrology in Mediterranean regions—a review

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INTRODUCTION

Dryland areas display high hydrological sensitivity to changes in their environment. This high sensitivity makes the survey of their water resources and hazards particularly crucial, not only in scientific terms, but also as a strategic aspect of technical and socio-political management. Being mainly semi-arid and arid, the Mediterranean basin and the Middle-East have major water needs (UNPD, 2006; Alcamo *et al.*, 2007; Iglesias *et al.*, 2007). During recent decades, the large increase in population, rise of living standards, development of irrigated agriculture, and new activities—especially tourism—have drastically changed the water uses. Future needs will be hard to satisfy as many aquifers are already overexploited and surface waters are endangered (Tal, 2006; Kundzewicz *et al.*, 2007; Murad *et al.*, 2007; Qadir *et al.*, 2007). According to the Plan Bleu (Margat & Treyer, 2004), 60% of the world's water-poorest population (i.e. with less than 1000 m^3 per capita per year) live in the southern and eastern parts of the Mediterranean basin. Therefore, improving the identification of the main hydrological processes, and their variability and changes, is essential for better management of the water resources, and for the day-to-day life of millions of people.

In recent decades, this increasing stress on the water balance has required management of local irregular resources to develop from the traditional, parsimonious management towards more intensive water resources exploitation. In many cases, the balance between water resources and needs is not achieved and numerous negative effects have emerged. Moreover, the regional climate change (Christensen *et al.*, 2007) may have major hydrological impacts, which need to be assessed and to which water management should be adapted (Kundzewicz *et al.*, 2007).

In the framework of the international conference "*Future of Drylands*" organized by UNESCO and the Tunisian authorities in June 2006, in Tunis, during the International Year of Deserts and Desertification (IYDD), the G-WADI network (http://gwadi.org) of the International Hydrological Programme (IHP) initiated a side event dedicated to these issues and with a focus on the Mediterranean region. Following this event, several papers were considered for publication in *Hydrological Sciences Journal* and, following peer review, seven are published in this Special Section (Hreiche *et al.*, 2007; Leduc *et al.*, 2007; Martín-Rosales *et al.*, 2007; McIntyre *et al.*, 2007; Nasri, 2007; Romagny & Riaux, 2007; Slimani *et al.*, 2007). These papers—as well as regular papers with similar focus, also published in this issue—cover several aspects of the range of current quantitative hydrological issues in the Mediterranean and Middle-East in relation to water management.

MAJOR HYDROLOGICAL CHANGES

Watershed changes

As in other dryland regions (Servat *et al.*, 2003), anthropogenic long-term changes are very important in Mediterranean and Middle-Eastern hydrology, either in terms of water requirements, or through changes in geography and land cover (Kundzewicz *et al.*, 2007; Rosenzweig *et al.*, 2007). Present water consumption for agriculture is 60% for the whole Mediterranean basin, and about 80% or more in the southern, eastern and northeastern parts. Transformations in agriculture (expansion of cultivation to southern semi-arid areas where pastoralism was usual, depopulation of remote mountains) and land-use intensification (overgrazing, land degradation, irrigation) are major changes (Puigdefabregas & Mendizabal, 1998; Qadir *et al.*, 2007). Anthropogenic deforestation (Martín-Rosales *et al.*, 2007) and forest fires (Lavee *et al.*, 1995; Inbar *et al.*, 1998; Candela *et al.*, 2005; Di Piazza *et al.*, 2007), also constitute a major change in land use.

Such land-use changes induce changes in surface runoff, erosion and groundwater (Benkhaled & Remini, 2003; Touaïbia & Achite, 2003; López-Moreno *et al.*, 2006; Lajili-Ghezal, 2007; Megnoufif *et al.*, 2007). More generally, as a result of climatic and anthropogenic shifts, hydrological fluxes and physical characteristics may evolve in the sense of desertification (Puigdefabregas & Mendizabal, 1998; Tooth, 2007; see also the "Desert science" dossier of http://www.scidev.net, and the "Desertification" web pages of FAO http://www.fao.org/desertification/). To store water and sediments, new soil and water conservation and water harvesting techniques, of various kinds and scales, have been developed (Tal, 2006; Qadir *et al.*, 2007). Similar traditional techniques historically underpinned Mediterranean civilizations (Mays *et al.*, 2007), and appeared to be very efficient both at the hillslope (Nasri *et al.*, 2004a) and upper stream (Fleskens *et al.*, 2005) levels, and through cascades within small watersheds (Schiettecatte *et al.*, 2005; Romagny & Riaux, 2007). With respect to modern developments, Nasri (2007) shows the considerable reduction in hillslope surface runoff by a modern terracing technique, which helps to store water in the field soil and reduce sediment yield downstream, whereas Nasri *et al.* (2004b), Kingumbi *et al.* (2007) and Leduc *et al.* (2007) assess and simulate the aggregated impacts at the level of larger basins.

Among modern techniques, dams of various sizes have been constructed to store water that naturally flowed out to the sea, as well as to help to cope with high inter-annual variability and to mitigate flood hazards. Because of silting, the lifetime of small dams may vary between 5 and 20 years (which emphasizes the need to develop techniques for sedimentation management), but is expected to be more than 100 years for large dams (Albergel *et al.*, 2004; De Araujo *et al.*, 2006; Remini & Wassila, 2006; Ben Mammou & Louati, 2007). Dams cause changes in downstream hydrology and geomorphology. The lack of sediment may lead to reduced soil fertility and a shortening of delta fans. The Ebro Delta, Spain, is an extreme example of this: it has expanded for the last millennium because of deforestation, but is now retreating because of the 340 dams that trap nearly all the sediment load (Vericat & Batalla, 2006). Furthermore, dams smooth natural hydrological variability and extremes, and, consequently, downstream rivers lose part of their flow capacity, thus aggravating flooding on the occasion of very extreme events. This also increases vulnerability because people are less conscious of flood hazards and develop flood plains for agriculture, industry, homes, etc., as Lebdi *et al.* (2006) and Zahar & Albergel (2006) showed for the northern Tunisian Wadi Mejerda basin. Similar problems have also been reported in Greece, where the idea of scheduled artificial flooding has been proposed as a mitigation measure (NTUA, 2007). Furthermore, this smoothing of flows reduces aquifer recharge through wadi (ephemeral stream) infiltration in the plains (Leduc *et al.*, 2007).

As an alternative to artificial reservoirs, which are costly and enhance evaporation, the exploitation of aquifers develops, often intensively. Cases of groundwater overexploitation are numerous. In Sierra de Crevillente, southern Spain, the water table dropped 250 m in 20 years (Martín-Rosales *et al.*, 2007). Such unsustainable practices, combined with inefficient use of energy for pumping from great depths, have also been reported in agricultural areas in Greece, where they cause additional problems such as extensive soil subsidence and deterioration of water quality in aquifers due to agricultural chemicals (NTUA, 2007). In the Tunisian Kairouan plain, overexploitation is severe (Ben Ammar *et al.*, 2006; Leduc *et al.*, 2007) because of agricultural intensification and as a result of the combination of multiple stakeholders and the behaviour of users (Feuillette *et al.*, 2003). When groundwater overexploitation exists in the vicinity of marine or brackish water, intrusion of these waters into freshwater aquifers is a major hazard (Paniconi *et al.*, 2001; Al-Agha *et al.*, 2004; Guhl *et al.*, 2006; Murad *et al.*, 2007; Fadlelmawla *et al.*, 2008). In such situations, sustainability is at great risk and conflicts between activities and users emerge. The aquifer may have many different users, which complicates the management and control in cases of overexploitation; in contrast, surface water reservoirs are usually managed by a single authority. Controlled recharge of aquifers may nevertheless be considered through dam outflow management and infiltration facilitation (Nazoumou & Besbes, 2000; Zammouri & Feki, 2005). Furthermore, the abundance of carbonate rocks in the Mediterranean basin frequently generates uncontrolled recharge of reservoir water to the underlying karst (Remini & Wassila, 2006; Ben Ammar *et al.*, 2006; Leduc *et al.*, 2007).

Climate change

The natural climate variability in the Mediterranean basin and the Middle East is very high (Xoplaki *et al.*, 2004; Lionello *et al.*, 2006; López-Moreno *et al.*, 2007) and related uncertainties are significant (Bacro & Chaouche, 2006; Koutsoyiannis & Montanari, 2007). To date, no uniform regional pattern has been identified across the Mediterranean region. The variety of climatic behaviour across this large geographical area, as well as the heterogeneity of studies and their data sets, uncertainties, statistical methods and interpretations, make the identification of a uniform change unlikely. Particular local changes already identified may contradict each other. Thus, from the survey of 50 stations during 70 years in Basilicata (southern Italy), Piccarreta *et al.*

(2006) identified a long-term decrease in rainfall. Yet, at the broader scale of the whole of Spain and Portugal, for the same period, Serrano *et al.* (1999) demonstrated the lack of any significant trend in 40 stations. In the same way, Sakiss *et al.* (1994) studied 43 long data sets over the whole of Tunisia and did not find any coherent trend. When looking at greater detail (number of rainy days, rainfall intensity, etc.), the same lack of coherent trends at the regional scale still persists. Alpert *et al.* (2002) showed changes in the distribution of lightest and heaviest rainfall for stations in Spain and Italy, whereas there were no changes in Israel and Cyprus. Martín-Rosales *et al.* (2007) emphasize the difficulty in distinguishing change from variability and larger anomalies in southeastern Spain. Changes that may have diverse hydrological impacts (Kundzewicz *et al.*, 2007) have been identified in some places; for instance, on rainfall erosivity in Sicily (D'Asaro *et al.*, 2007) and the spatial dimensions of storms in central Tunisia (Kingumbi *et al.*, 2005), as well as on water balance terms such as evaporation in Israel (Möller & Stanhill, 2007).

Changes in rainfall obviously affect the river flow. Thus, changes in runoff may also help identify a possible climatic modification. For instance, the longest river flow records of Greece indicate a falling trend since 1920 (Koutsoyiannis & Mamassis, 1998; Koutsoyiannis *et al.*, 2007), which is consistent with a trend in rainfall on the same area but not over the whole of Greece. But the detection of runoff changes is more complex than in rainfall time series, mainly because of anthropogenic influences such as the increase in surface water abstractions and groundwater pumping, such as in the Ebro River in Spain where a decrease in runoff by more than 60% is observed (Skliris *et al.*, 2007). An additional complexity may arise from the fact that large river basins may extend over geographical areas with different climates. The most distinctive example is the Nile River, the most important river flowing into the Mediterranean Sea, whose basin encompasses a much larger area—as far south as Lake Victoria (Sutcliffe & Petersen, 2007)—and thus integrates climatic behaviour and changes over tropical and subtropical areas. The water level records of the Nile are a unique case in history as they extend for several centuries, while additional documentation of its flow covers several millennia. These records indicate huge climatic variability at large time scales such as hundreds of years or more (e.g. Koutsoyiannis, 2006). Given that similar hydro-climatic variability is observed in other time series, too, and is largely unexplained, the diverse aspects of climate changes are difficult to attribute and assess (Christensen *et al.*, 2007; Koutsoyiannis *et al.*, 2007; Rosenzweig *et al.*, 2007).

Global circulation models (GCM) still present "substantial uncertainties" (Christensen *et al.*, 2007), and have problems in simulating the extreme variability in time and space, which prevent them from representing the past, present and future Mediterranean climate with satisfactory accuracy. For instance, in a major catchment of Greece, Koutsoyiannis *et al.* (2007) found that GCM outputs underestimate past over-annual variability of water resources and provide future projections that are too stable in comparison to the much wider climatic uncertainty limits under natural variability. Slimani *et al.* (2007), Jebari *et al.* (2007) and Kingumbi *et al.* (2005) provide multi-scale space–time analyses of rainfall over the whole of Tunisia and, more specifically, over the Tunisian Dorsale mountain range. This combined analysis provides a reference for assessing the space–time dimensions of climate change in the future, both over part of the Mediterranean–Sahara transition and over a strategic mountainous region. The influence of relief on the circulation of wet air masses is identified (Mamassis & Koutsoyiannis, 1996; Romero *et al.*, 1999; Xoplaki *et al.*, 2004; Lionello *et al.*, 2006; López-Moreno *et al.*, 2007), and it is shown that changes in trajectories may lead to major spatio-temporal redistribution of rainfall, with many complex effects in the downscaling of the general regional projected rainfall decrease (de Wit & Stankiewicz, 2006; Christensen *et al.*, 2007). Furthermore, changes in snow-dominated regimes appear to be a crucial issue (Christensen *et al.*, 2007; Rosenzweig *et al.*, 2007), given the influence of snow on water resources in several Mediterranean areas such as Lebanon (Aouad-Rizk *et al.*, 2005; Corbane *et al.*, 2005; Hreiche *et al.*, 2007), Turkey (Tekeli *et al.*, 2005), Spain (López-Moreno, 2004) and Morocco (Chaponnière *et al.*, 2007).

DATA AND METHODS

The data scarcity in most areas of the Mediterranean basin and Middle-East is a great handicap to studying the changes in water resources at relevant scales (Sivapalan *et al.*, 2003). Knowledge is nevertheless improved in different ways. Firstly, there is an emphasis on data: large data sets are compiled (Jebari *et al.*, 2007; Slimani *et al.*, 2007); dedicated experimental data of various types are collected (Leduc *et al.*, 2007; Megnounif *et al.*, 2007; Nasri, 2007; Romagny & Riaux, 2007); data scattered among various studies and authorities are made coherent (Bouri *et al.*, 2007; Kingumbi *et al.*, 2007; Leduc *et al.*, 2007; Martín-Rosales *et al.*, 2007; Fadlelmawla *et al.*, 2008).

Secondly, complementary studies are developed on the same basins, which then become references for studying actual hydrology–water management aspects, even if not developed as proper experimental watersheds. This is particularly the case in central Tunisia, with studies dedicated to the Wadi Merguellil basin (Nazoumou & Besbes, 2000; Feuillette *et al.*, 2003; Cudennec *et al.*, 2005; Kingumbi *et al.*, 2005, 2007; Ben Ammar *et al.*, 2006; Leduc *et al.*, 2007), and to the network of small basins recently drained by hill reservoirs (Albergel *et al.*, 2004; Nasri *et al.*, 2004b; Zammouri & Feki, 2005; Jebari *et al.*, 2007; Lajili-Ghezal, 2007; Nasri, 2007).

Thirdly, effort is focused on methodology: robust methods are developed to provide a compromise between applicability and accuracy, particularly in the field of rainfall–runoff modelling (Camarasa & Tilford, 2002; Benkaci Ali & Dechemi, 2004; Nasri *et al.*, 2004b; Cudennec *et al.*, 2005; Hreiche *et al.*, 2007; Moussa *et al.*, 2007; McIntyre *et al.*, 2007; Ouachani *et al.*, 2007; Chaponnière *et al.*, 2007), which is a major concern in semi-arid and arid basins (Pilgrim *et al.*, 1988; Hughes, 1995; Sharma & Murthy, 1998; Wheater *et al.*, 2006); complementary methods are combined, particularly in hydrogeology (Kamel *et al.*, 2006; Bouri *et al.*, 2007; Leduc *et al.* 2007; Fadlelmawla *et al.*, 2008), or between hydrological and social sciences (Barriendos & Rodrigo, 2006; Brewer *et al.*, 2007; Martín-Rosales *et al.*, 2007; Romagny & Riaux, 2007); models and analyses are coupled, for instance between surface water and groundwater hydrology (Rozos *et al.*, 2004; Bouri *et al.*, 2007; Kingumbi *et al.*, 2007), and between stochastic and dynamic approaches (Hreiche *et al.*, 2007; Kingumbi *et al.*, 2007; Lajili-Ghezal, 2007); and comparisons are developed to identify specificities (Möller & Stanhill, 2007; Romagny & Riaux, 2007).

STRUCTURES AND SCALES

Geographical and geometric limits

Because of the importance of groundwater resources in semi-arid and arid contexts, a major issue is the identification of hydrogeological systems. Concerns particularly relate to the limits of hydrogeological basins and recharge areas (Zouhri *et al.*, 2004; Bonacci *et al.*, 2006; Kingumbi *et al.*, 2007; Leduc *et al.*, 2007; Fadlelmawla *et al.*, 2008); to the shape of the interface between freshwater and saline water (Al-Agha *et al.*, 2004; Guhl *et al.*, 2006; Fadlelmawla *et al.*, 2008); and to the multilayer structure (Kamel *et al.*, 2006; Bouri *et al.*, 2007).

Time

Due to high variability and ephemeral events, dryland hydrology involves strong non-linearity including thresholds (Nouh, 2006; Hreiche *et al.*, 2007; Kingumbi *et al.*, 2007; Lajili-Ghezal, 2007; McIntyre *et al.*, 2007; Nasri, 2007), and sometimes hysteresis (Benkhaled & Remini, 2003; Megnounif *et al.*, 2007). These may lead to the activation of some processes and compartments only during extreme events, such as aquifer recharge (Nazoumou & Besbes, 2000; Ben Ammar *et al.*, 2006; Leduc *et al.*, 2007), or of a cascade system (Nasri *et al.*, 2004a; Nasri, 2007; Romagny & Riaux, 2007).

At longer time scales, changes may be sudden or progressive, as are their impacts. Fires are particularly abrupt (Inbar *et al.*, 1998; Candela *et al.*, 2005; Di Piazza *et al.*, 2007) and have immediate impacts followed by a gradual return to initial conditions (Di Piazza *et al.*, 2007). Nasri (2007) quantifies the immediate impacts of sudden hillslope terracing, but also raises the question of the terraces' ageing, which implies marked changes in the long term. Ben Ammar *et al.* (2006) and Leduc *et al.* (2007) consider the construction and filling of a large dam and its hydrogeological consequences, whose time scales are very long, in relation to the aquifer dimensions and to the characteristic process time scales: impacts are thus not independent of other changes occurring during the same periods, especially water withdrawals for intensive irrigation.

Kingumbi *et al.* (2007), Leduc *et al.* (2007) and Martín-Rosales *et al.* (2007) deal with the impacts of progressive changes in watersheds through the setting up of numerous water and soil conservation, and water harvesting techniques. The historical changes in land and water use appear to be difficult to assess and correlate to the hydro-climatic variability. Lebdi *et al.* (2006) and Zahar *et al.* (2006) consider the progressive change in the hydraulic capacities as regards extreme events, and the shifts in flood hazards. Due to the spatial heterogeneity of such progressive changes, the progressive impact assessment often interferes with the question of aggregation of individual and local impacts. To address such issues, historical hydrology (Barriendos & Rodrigo, 2006; Brázdil & Kundzewicz, 2006) appears to be a major perspective.

Space–time

Spatial and temporal dimensions are determinants for the characterization of processes, the assessment of changes and the identification of structures. This is generic and can be illustrated by the following hydro-meteorological aspects. Spatial fields of rainfall data (Lana *et al.*, 2004; Subyani, 2004; Kingumbi *et al.*, 2005; Jebari *et al.*, 2007; Slimani *et al.*, 2007) and drought data (Sirdaş & Şen, 2003; Bayazit & Onöz, 2005; Vicente-Serrano, 2006; Brewer *et al.*, 2007) can be analysed in space through various methods, such as geostatistics, spatial correlation, empirical orthogonal functions, clustering or regionalisation. Such analyses, eventually carried out at various time steps and scales, allow the identification of geographical determinants and structures. Through diachronic use, they could help towards the identification of complex aspects of climate change. The spatio-temporal organization of meteorological and climatic driving forces is a determinant for hydrological responses (Mamassis & Koutsoyiannis, 1996; Bull *et al.*, 2000; Camarasa & Tilford, 2002; Arnaud *et al.*, 2002; Neppel *et al.*, 2003; Bargaoui & Chechoub, 2004; Gaume *et al.*, 2004; Cudennec *et al.*, 2005; McIntyre *et al.*, 2007), mainly via the way in which the river basin structure is stimulated (Cudennec, 2007; Moussa, 2007). Furthermore, multi-site analyses of statistical distributions provide a decisive additional frequency dimension (De Luis *et al.*, 2000; Bayazit & Onöz, 2005; Dominguez Mora *et al.*, 2005; Pujol *et al.*, 2007). Consequently, changes in the spatio-temporal organization of meteorological events and climatic variables, with respect to the structure of a given river basin, should have hydrological impacts, especially in terms of water resources and the redistribution of hazards in space and time.

FINAL REMARKS

This Special Section illustrates quantitatively some of the range of hydrological changes in the Mediterranean basin and the Middle-East. Due to the high sensitivity of the hydrology, and the demographic and associated pressures, hydrological changes are, and will be, a combination of climate-induced and anthropogenic changes, related to land and water management. Hydrological studies must be enhanced at various scales from the local to the sub-continental. Support, coordination of studies and co-operation between scientists; data collection, homogenization and sharing; and knowledge communication should be geared towards assessment and prediction of changes, as well as towards adaptive management and mitigation strategies. Hydrological knowledge must also be disseminated among stakeholders (Koutsoyiannis & Kundzewicz, 2007), including policy makers as regards potential emerging water-related conflicts. The Tunis 2006 side event was organized as a modest contribution to this general approach. The International Association of Hydrological Sciences (IAHS) and its official journal, *Hydrological Sciences Journal* (*HSJ*), share this philosophy; hence, *HSJ*, having a history of publishing papers from the Mediterranean basin and the Middle East, was chosen as the vehicle for publishing this Special Section.

Acknowledgements The Tunis side event was organized by the research team G-EAU and the IRD office in Tunis, with the help of UNESCO and Tunisian authorities. Sponsorships of G-WADI, IAHS, and the EU FP6 project AquaStress are acknowledged. Thanks are extended to Dr A. Lipponen (UNESCO), Prof. H. Wheater (Imperial College London, G-WADI) and Prof. G. M. Zuppi (University of Venice). The authors wish to thank the Editor, Prof. Z. W. Kundzewicz, for his confidence and support, the Production Editor, Ms F. Watkins, for her excellent cooperation and Dr Cate Gardner for her suggestions. Sincere thanks are also due to all authors of the papers and reviewers who worked hard on the quality of this Special Section.

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