Chapter 3

Impacts on water and soils

Chapter coordinator

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Abstract

This chapter presents research outputs concerning the expected relative impacts of anthropogenic and climate changes on water and soil resources in the Mediterranean region, and their associated vulnerabilities. First, in subchapter 2.3.1., the current methods and their limits are outlined. The main projected changes due to the rise in temperature concern evapotranspiration (increased climatic demand, more water limiting cases) and snowfall (less snow, melting occurs sooner), as well as the possible increased intensity and frequency of extreme events (droughts and floods, subchapter 2.3.2). Rainfed agriculture is particularly threatened. The expected impacts of changes in precipitation patterns and land use on soil erosion are assessed in subchapter 2.3.3. The challenge of foreseeing the impacts of extreme rainfall events on floods is documented in subchapter 2.3.4. The difficulty involved in maintaining long term monitoring of those resources, with little funding available to support a dense gauging network, encourages us to develop alternative observation systems based on distributed data acquired through remote sensing (2.3.2) or post-event inquiries (2.3.4), for example. Current human activities may occasionally reduce certain vulnerabilities

(for example through soil and water conservation systems) but more often exacerbate the negative impacts of climate change on soil and water resources; for example, unregulated groundwater extraction (subchapter 2.3.5), intensification of agriculture (2.3.2) usually amplify rather than mitigate the factors responsible for overexploitation of available blue and green, renewable and fossil water, or increased soil loss (2.3.3). Overall, the uncertainties on the various subparts of the coupled man-earth system make it difficult to build, if not reliable, then at least realistic scenarios for the evolution of water and soil resources even for the coming decades. Like for GHG emissions, several ongoing projects under the AllEnvi umbrella try to identify a range of individual evolution scenarios based on actual mechanisms and hydrological models that are calibrated and evaluated using hydrological extremes extracted from recent history (2.3.1).

Résumé

Ce chapitre présente les résultats de recherche concernant l'impact relatif attendu des changements anthropiques et climatiques sur les ressources en eau et en sols dans la région méditerranéenne, et leurs vulnérabilités associées. Les méthodes actuelles et leurs limites sont d'abord décrites dans le sous-chapitre 2.3.1. A travers l'élévation de température, les plus grand changements concernent l'évapotranspiration (plus grande demande climatique, stress hydrique plus fréquent) et les chutes de neige (moins de neige, la fonte se produit plus tôt), ainsi que la probable augmentation en nombre et en intensité des événements extrêmes (sécheresse, inondation, sous-chapitre 2.3. 2). Une menace particulière existe pour l'agriculture pluviale. L'impact sur l'érosion des sols des changements attendus dans la distribution des précipitations et les usages des terres est évalué dans le sous-chapitre 2.3.3. Le défi que constitue le besoin d'anticiper les impacts des événements précipitants extrêmes sur le risque d'inondation est documenté dans le sous-chapitre 2.3.4. La difficulté à maintenir une surveillance à long terme de ces ressources, avec peu de financements disponibles pour garantir un réseau de jaugeage suffisamment dense, nous encourage à développer des systèmes d'observation alternatifs, sur la base des données distribuées acquises par exemple par télédétection (2.3.2) ou à travers des enquêtes post-événement (2.3.4). Les activités humaines réduisent parfois certaines vulnérabilités (par exemple grâce à des ouvrages de conservation), mais amplifient le plus souvent les impacts négatifs du changement climatique sur les ressources en sols et en eaux: l'extraction non réglementée des eaux souterraines (sous-chapitre 2.3.5), l'intensification de l'agriculture (2.3.2) sont en général des facteurs aggravants plutôt que des facteurs d'atténuation pour la surexploitation de l'eau disponible bleue et verte, renouvelable et fossile, et participent de l'accroissement de la perte de sol. Dans l'ensemble, compte tenu des incertitudes sur les différents

sous-ensembles du système couplé Homme-Milieu, il est difficile de construire des scénarios fiables ou même réalistes pour l'évolution des ressources en eaux et en sols, même pour les prochaines décennies. Plusieurs projets en cours sous l'égide d'Allenvi proposent, de manière similaire à ce qui est fait pour les émissions de GES, des trajectoires limites basées sur les mécanismes à l'œuvre actuellement et des modèles hydrologiques calés et évalués sur les différents extrêmes climatiques identifiés pour des périodes récentes (2.3.1).

Sub-chapter 2.3.1

Hydrological impacts of climate change in North African countries

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Introduction

Countries in North Africa with a semi-arid Mediterranean climate are facing water scarcity and high inter-annual variability of their water resources. Many dams and reservoirs have been built in recent decades to collect surface water and improve the management of existing water resources (Figure 1). However climate projections for this region indicate a possible decrease in precipitation together with an increase in temperature that could result in increased evaporation (Schilling et al., 2012). Evaluating the potential impacts of climate change on water resources is thus of particular importance in this region. To quantify the impacts of climate change on hydrology, climate model outputs need to be combined with the outputs of hydrological models. Climate models provide simulations up to the year 2100, either at large scale (global circulation models) or at regional scale (regional climate models). Most climate models outputs cannot be used directly in hydrological models because the spatial scales do not match or because of a systematic bias in the model outputs, particularly for precipitation. Downscaling or bias-correction techniques thus need to be applied before making future hydrological projections. This chapter presents the main results obtained in the ENVIMED 'CLIHMAG' project funded by MISTRALS for the period 2014-2015. Three different issues are addressed: the validity of standard downscaling methods in a semi-arid context, the reliability of hydrological models in different climate conditions, and effect of the climate change signal on water resources in North African basins.

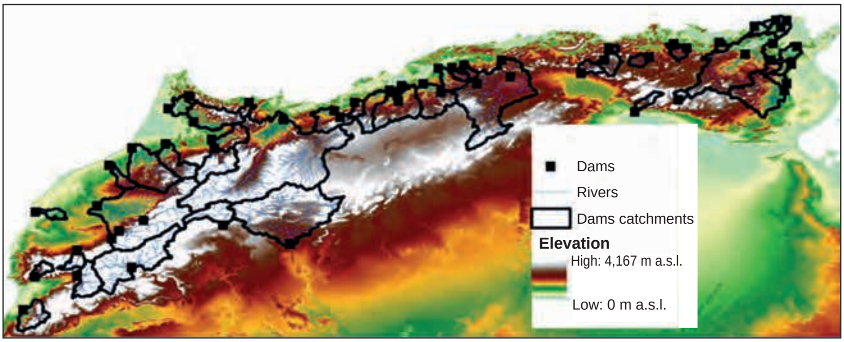

Figure 1
Map of the 47 biggest dams in North Africa.

The observed data needed to run the hydrological model used to address these issues came from a variety of representative catchments. These include the Loukkos (1785 km²) catchment, upstream of the Makhazine dam (the 6th largest dam in the country) in northern Morocco, the main tributary of the Oum Er Rbia basin, the El Abid (4980 km²) catchment, upstream of the Bin Ouidane dam (largest hydro-power production in Morocco), and in the high-altitude (up to 4167m) Rheraya catchment (225 km²) upstream of the Tensift catchment in southern Morocco. In Tunisia, the catchments selected are representative of the main hydrographical basins that produce most surface water resources. They include the Rhezala catchment (138 km²) in the Medjerda basin, upstream of the Sidi Salem dam (the largest in Tunisia), the Sejnane (376 km²), Joumine (231 km²), Melah (315 km²) and Maaden (145 km²) catchments in the north and Ichkeul basins and the El Abid catchment (81 km²) in the Cap Bon region.

Are bias-correction methods for climate model outputs valid under semi-arid conditions?

Two kinds of climate simulations are available for studies on climate change impacts, general circulation models (GCM) running at a large scale (100-300 km) or regional climate models (RCM), driven at their boundary conditions by GCMs and running at the regional scale (12-25 km). In the Coordinated Regional Climate Downscaling Experiment (CORDEX, www.cordex.org), RCM simulations at a fine spatial scale (12 km) are becoming available for most regions of the world. North Africa is covered both by the EuroCORDEX and the MedCORDEX domains at a high resolution (12 km). This fine spatial scale allows orographic processes to be more realistically represented and improves the simulation of extreme rainfall events, which contribute a significant proportion of total precipitation in semi-arid areas. However, despite improvements in the models thanks to finer spatial resolution, precipitation is generally underestimated by models and cannot be used directly in hydrological models. For that reason, impact studies require downscaling and/or bias correction to reduce the gap between model outputs and observations, usually averaged or interpolated at the catchment scale for hydrological applications. A correction or a transfer function is often applied to climate model outputs, estimated in the past and applied to future simulations, assuming that the correction will remain valid in the future.

This rather strong assumption of stationarity of the correction applied to climate model outputs can be validated at least during historical periods; such validation has been performed for different catchments in North Africa. The results suggest that bias correction methods such as the quantile-mapping method, which is widely used in hydrological impact studies, may be difficult to validate in semi-arid climates due to the limited number of rainy days, in particular during summer, and to the significant inter-annual variability of precipitation, which is typical of the Mediterranean climate (Tramblay et al. 2013; Foughali et al. 2015). In the case of a shift towards drier conditions or different time periods, the methods may not be able to correct the model bias with sufficient accuracy, particularly for precipitation. If the bias correction methods are not properly validated using historical climate conditions prior to being used in future projections, this could affect the climate change signal. As an alternative to correction methods, other methods can provide climate scenarios based on the perturbation of the observed data series by a climate change signal.

A method that is commonly used for climate change impact studies is the change factor method sometimes referred to as the “delta change” method. It consists in modifying the observed data series (temperature, precipitation, etc.) by a climate change factor in order to produce climate scenarios (Tramblay et al. 2013). These types of methods range from simple ones that assume a monthly change factor, to more complex approaches perturbing the whole distribution of observations and resampling of the original sequences to account for changes in temporal variability. These methods do not rely on the stationary assumption of model biases and do not modify the climate model outputs. Consequently, they can be considered as more robust and should be preferred in cases where other approaches cannot be satisfactorily validated.

Are hydrological models sufficiently robust to make future projections?

Different types of hydrological models exist that rely either on conceptual or physically-based structures. Physically-based models rely on the characteristics of the catchments and require many field observations, but these are rarely available, particularly in data-sparse regions and developing countries. Conversely, conceptual models usually require only time series of precipitation, evapotranspiration and discharge and are widely used in operational applications such as water resources or dam management. We tested a range of hydrological models (GR4J, GR2M, IHACRES, HBV, MWBM, BBH) commonly used for water resources management and research applications in North Africa under contrasted climatic conditions. Most hydrological models used in practical applications have a conceptual structure and require calibration (i.e. the model parameters are inferred using observed discharge data). However, calibration may be influenced by the choice of the time period of observations and therefore strongly impact the climate change projections.

The analysis of model robustness for the test catchments indicated that the difference in climate between calibration and validation gradually affect model performances. Although the model parameters tested were shown to be transferable towards wetter and/or colder conditions, their efficiency decreased when more contrasted climate conditions than those in the period used for calibration are experienced (for example in Tunisia, a threshold of transferability has been identified when the future change in temperatures exceeds +1.5 °C and the decrease in precipitation is more than -20%, Dakhlaoui et al. 2015). As a consequence, in studies on the impacts of climate change, we recommend choosing calibration periods when the climate conditions resemble future climate conditions, as this could significantly reduce hydrological modelling uncertainty.

How will projected climate change affect water resources?

The projected impacts on water resources were analyzed using an ensemble of medium (50 km) and high (12 km) resolution simulations from the EuroCORDEX and MedCORDEX experiments. The multi-model ensemble composed of different RCMs driven by different GCMs made it possible to evaluate the uncertainties stemming from the different simulations. Two emission scenarios were used, the representative concentration pathways (RCP) 4.5 and 8.5. They describe future climates that are considered possible depending on the quantity of greenhouse gases emitted in the years to come. In RCP 4.5 emissions peak around the year 2040, whereas in the most pessimistic scenario (RCP 8.5), emissions continue to rise throughout the 21st century.

The results at regional scale confirmed those of previous studies indicating a general increase in temperature associated with a decrease in precipitation (Bargaoui et al. 2014). However, the high resolution simulations enabled better spatial characterization of the projected changes. As shown in Figure 2, the relative changes in precipitation follow a clear east-to-west gradient with precipitation projected to decrease by 10% on average in basins in northern Tunisia to a 40% decrease in southern Morocco. On the opposite, the projected changes in temperature are much more homogeneous over North Africa (Figure 3) and depend mainly on the different emission scenarios considered (RCP 4.5 and RCP 8.5). In addition, potential evapotranspiration is projected to increase (+10% to +30%) in most areas, these changes being modulated by both land cover and land use. As a consequence, reduced precipitation associated with increased evaporation leads to less surface water resources in all North African catchments in both scenarios. According to the multi-model ensemble, these changes are robust since all models agree on the same decreasing trend. The change in precipitation will have the strongest impact on water resources, since North African catchments are water-limited rather than energy-limited.

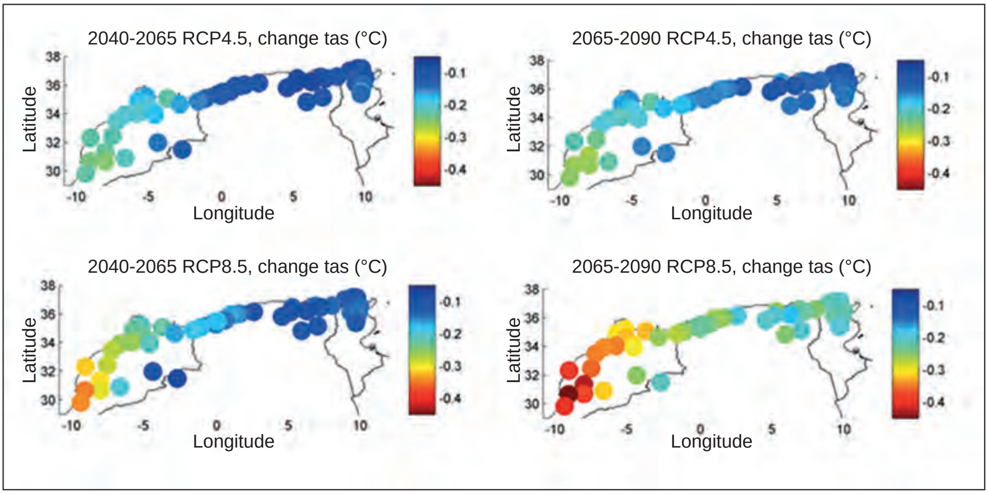

Figure 2
Future changes in precipitation in the 47 main dam catchments in North Africa, simulated by the SMHI-RCA4 regional climate model driven by 5 global climate models (CNRM, IPSL, HADGEM, ECEARTH, MPI) under the emission scenarios RCP 4.5 and 8.5.

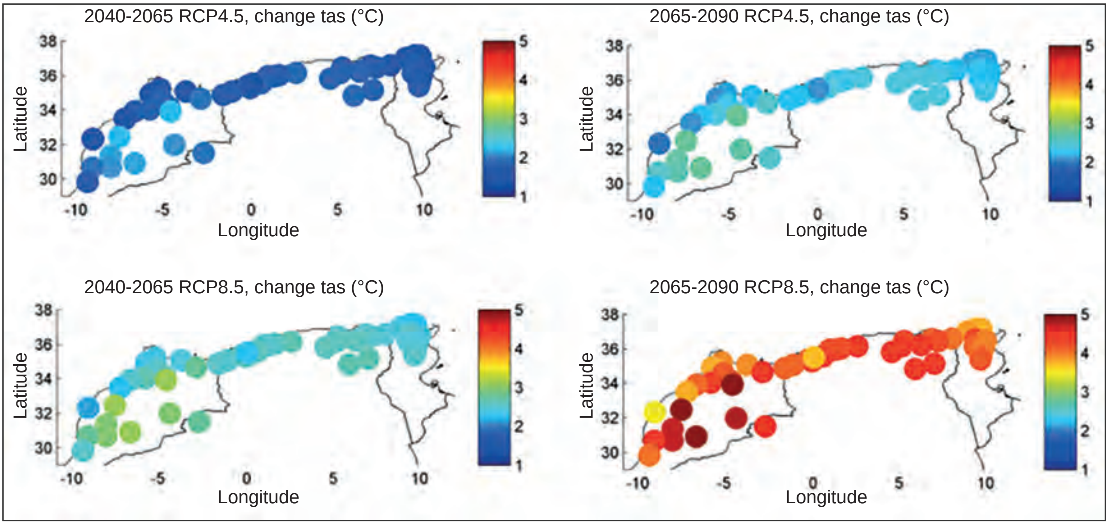

Figure 3
Future changes in temperature in the 47 main dam catchments in North Africa, simulated by the SMHI-RCA4 regional climate model driven by 5 global climate models (CNRM, IPSL, HADGEM, ECEARTH, MPI) under the emission scenarios RCP 4.5 and 8.5.

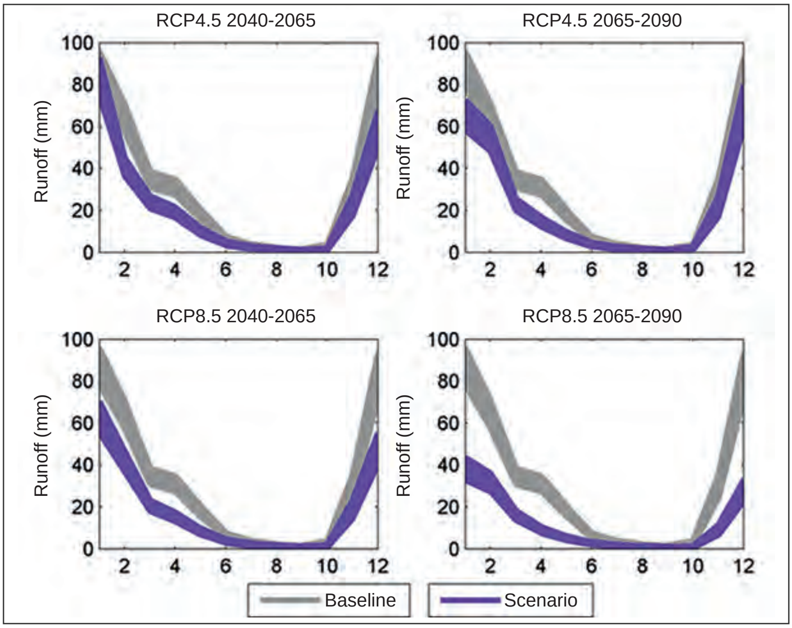

Figure 4
Future changes in mean monthly runoff at the Makhazine dam (north Morocco). The band width indicates the uncertainty on model projections (simulated by the SMHI-RCA4 regional climate model driven by 5 global climate models: CNRM, IPSL, HADGEM, ECEARTH, MPI).

We also analyzed the hydrological impact of the projected changes at the scale of the representative catchments considered in the ENVIMED CLIHMAG project. The results we obtained are illustrated by two examples of runoff projections presented for a catchment located in northern (Figure 4) and southern Morocco (Figure 5). For catchments located in the most humid areas, covering north Morocco, Algeria and Tunisia, the climate change signal is toward a reduction of 10% to 20% in precipitation, and as shown in Figure 4 for the mid-term time horizon (2040-2065), and in RCP 4.5, in most seasons, it is hard to distinguish between climate change, natural variability and modelling uncertainties. However in the most pessimistic emission scenario (RCP 8.5), the projected decline in surface water is significant in winter and spring. Conversely, in the snow-dominated catchments mainly located in the Atlas Mountains in southern Morocco (Marchane et al. 2016), a much stronger climate change signal points to a major decrease in spring runoff associated with a reduced snow cover (Figure 5). This could have serious consequences since these arid regions depend to a large extent on the water resources provided by the mountain ranges.

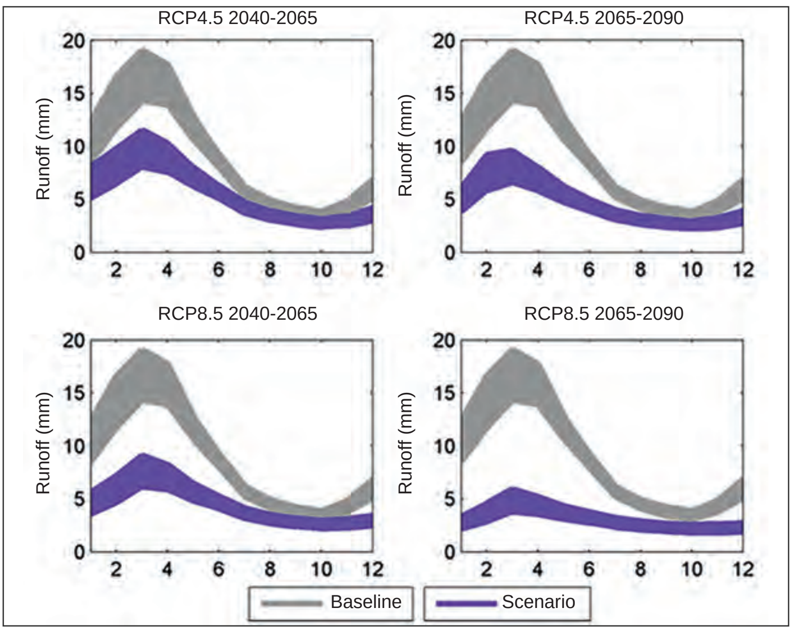

Figure 5
Future changes in mean monthly runoff for the Bin Ouidane dam (south Morocco). The band width indicates the uncertainty on model projections (simulated by the SMHI-RCA4 regional climate model driven by 5 global climate models: CNRM, IPSL, HADGEM, ECEARTH, MPI).

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Sub-chapter 2.3.2

Water resources in South Mediterranean catchments

Assessing climatic drivers and impacts

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Climate change

Positive trends in mean temperatures and a decrease in the number and amplitude of cold outbreaks have already affected all North African countries (Driouech et al., 2013). A global data set of near-surface meteorological variables was used to assess the long-term changes in temperature and precipitation in North Africa in the 20th century (Szczypta et al. in prep). The analysis revealed a significant increase (0.9 °C) in mean temperature between 1900 and 2010 (Figure 1). The increase was larger in spring (+1 °C) than in winter (+ 0.4 °C), except over the northeastern part of the region, where the increase remained high (+ 1.2 °C) throughout the year. The observed change in precipitation was less homogeneous over space and time but identified a hot-spot in northern Morocco. In addition to the aforementioned historical study, under the RCP2.6 low emission scenario, projected warming should reach 2 °C to 3.5 °C (from the coasts to inland areas) by mid-century and under the RCP8.5 high emission scenario, 3.5 °C to 5.5 °C. This goes hand in hand with an increase in the mean annual number of hot days. The original climate scenarios have been downscaled for two local stations (Marrakech, Morocco and Kairouan, Tunisia) in order to debias the original model simulations. In the moderate emission scenarios, similar trends are highlighted locally with an average increase in temperature of 1 °C by 2030, and of up to 1.5 °C by 2050 for both Marrakech and Kairouan. This increase should affect the warmest months of the year the most. Over Morocco, the projected increase in evapotranspiration varies from 10% to 20% under the RCP8.5 scenario for the whole crop season and should be also higher in spring. At the regional scale, the change in precipitation is more uncertain due to an observed divergence between model simulations compounded by significant inter-annual variability. However, significant reductions in precipitation are projected over the northern parts of Algeria and of Morocco; the wettest and largest agricultural areas in the region. A decrease of about 15% to 20% is projected by the mid-century under the RCP8.5 scenario and more severe reductions are projected for the second half of this century. The reduction is projected to be the most pronounced in spring and fall with probably dramatic consequences for water availability in these key periods of the agricultural season.

Anticipated societal changes

The population of southern Mediterranean countries will almost double by 2050, thereby threatening the fragile balance between water availability and human demand and, more specifically food security. At the 2025 horizon, agricultural demand could increase by 25% in response to the predicted population growth combined with the expected decrease in precipitation and rise in temperature at key phenological stages of crops in spring, while urbanization and economic development will encourage competition among sectors. The replacement of traditional Mediterranean crops (wheat) by more financially attractive crops but that also consume more water (maize, tree crops) will lead to major changes in water use patterns. In particular, the current extension and intensification of tree crops will further constrain agricultural water demand, especially during the hottest months. In addition, secure access to water from dams and water transfer channels is now threatened by dam silting and recurrent droughts like those at the beginning

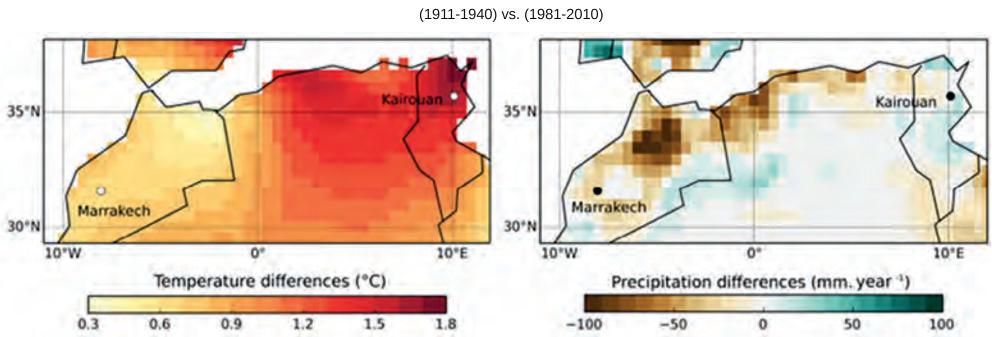

Figure 1
Historical analysis: differences of mean temperatures (left)/precipitation (right) between 1911-1940 and 1981-2010 at a 0.5° resolution from the Global Soil Wetness Project Phase 3 (GSWP3) from Szczypta et al., in prep.

Box 1
Observational issues

Long term observations are essential both for resource management and for hydrological model development and calibration over a wide range of climate conditions including extremes that are likely to become frequent in the future. Current water resources observation systems were thought to provide a good picture of available supply at the catchment outflow locations but are affected by loss of data quality, a decrease in the number of gauging stations, and the lack of available data since the 1980s. Upstream processes such as snowpack dynamics and subsurface flows that contribute to groundwater recharge, and downstream usage, are poorly monitored. Some integrated, long-term observatories of water resources that aim to complement the actual operational network exist, in particular in the Tensift and the Merguellil regions, but these successful initiatives need to be multiplied, strengthened and unified around an integrated regional observation system. Groundwater recharge processes (along *wadis*, by return of irrigation water, by subsurface flows or artificial through augmented streambeds) are currently largely unknown and should be the focus of scientific studies, in particular based on geochemical tracers. Non-conventional observations such as remote sensing and new innovative experimental designs based on low-cost *in situ* sensors should be promoted in these ungauged basins. Remote sensing will undergo a true revolution with the recent launch of the Copernicus constellation that will provide - free of charge - a large quantity of observations to enable monitoring of key variables for water resources management such as the extent of snow covered areas, soil moisture, land cover and use, surface water reservoirs, or crop dynamics. Despite the unprecedented availability of remote sensing data, their use by managers and stakeholders is still limited by their belief that the products are not suited to their specific needs. In practice, however, this is mostly due to lack of adequate training.

of the 2000s. As a result of the reduction in surface water, of agricultural extension and of easier access to water through boreholes (which are often neither registered nor monitored), groundwater is facing increasing pressure leading to groundwater depletion in the order of one to two meters per year with complete exhaustion at several locations. One of the potential consequences is farmer fragmentation resulting from the exclusion of small-scale farmers who do not have financial means to dig deeper and deeper wells. The intensification of agriculture in the plains may also increase societal tensions as the associated increase in water demand could become incompatible with the allocation of water to other sectors and with the ancestral water rights of upstream populations. Finally, the rapid pace of observed and anticipated societal changes are likely to have more effect on water resources than climate change in the medium term (2030), but the latter could have a greater impact at longer time scales.

The water tower in the mountain range

Each winter, large amounts of water are stored as snow in the highest mountainous areas of the Mediterranean. In the Tensift region, up to 50% of runoff is attributed to snow melt. Due to already observed rise in temperature, the snowline is rising in the Tensift region, with less water being stored as snow. This could be associated with a more rapid transfer of a larger proportion of precipitation downstream, which could rapidly challenge the existing storage capacity. Due to the rise in temperature, melt rates are also increasing and the snow is melting earlier than in the past in lower elevation areas. Early melt and reduced snow storage further reduce low flow discharge, could increase the number of days the *wadis* are dry and threaten the use surface irrigation systems in particular for tree crops in summer. In addition, in contrast to rainfall, the slow release of water due to melting enhances infiltration over runoff and reduces the return of water to the atmosphere by evaporation. Sublimation, loss of snow that does not contribute to runoff, is usually small, but is subject to marked interannual variability (Boudhar et al. 2015); it is not yet clear if climate change (through changes in wind intensity and air humidity) will increase or reduce sublimation, while current best estimates are that can account for up to 20% of total snow loss.

A better understanding of the links between upstream and downstream processes is essential to enable water planning, as water use and the upstream supply can significantly affect water availability downstream. On the other hand, a change that occurs upstream can also sometimes address an issue that occurs downstream. Several key processes that contribute to groundwater recharge occur at the upstream/downstream interface since recharge of basin aquifers through direct infiltration of rainfall is generally limited, as observed in Tensift region (Boukhari et al. 2015). Population density and upstream water use is increasing with unmonitored uptakes along the river to irrigate agriculture in the foothills. The expected changes in the snow/rain partition and uncontrolled water uptake may directly affect the timing and amount of water available downstream as well as indirectly through changes in the groundwater recharge rates.

Improving water irrigation planning

Although ambitious policies to convert to water saving techniques are currently being promoted, the traditional flood irrigation method, whose efficiency does not exceed 50%, remains the dominant practice in the southern Mediterranean. Improving this efficiency could be one way to tackle the expected reduction in water allocated to agriculture in the future.

Experimental studies on the main crops grown in the Mediterranean region (wheat, olives, oranges, etc.) carried out in the Tensift (Morocco) and Merguellil (Tunisia) regions called the efficiency of drip irrigation into question by showing that percolation losses from fields equipped with drip irrigation can equal and even exceed evaporation losses from flood-irrigated fields (Chehbouni et al., 2008; Jarlan et al., 2015). The lack of farmer training combined with the absence of complementary water regulation policies could thus have the unexpected consequence of increasing water losses for the plant. Another risk associated with conversion is agricultural intensification, which has already taken place in some locations and could also weaken or even negate the intended effect. Another important issue is related to the optimal choice of sowing date: fields in which the crops are sowed early would benefit from rainfall that is more effective at the beginning of the season and avoid the high evapotranspiration losses at the end of the season (April–May) which coincide with the grain filling stage of wheat, a critical stage for grain production. Modeling and experimental studies on wheat in Morocco revealed that the quantity of irrigation water required was always more than 100 mm (38%) higher in the case of late sowing. Deficit irrigation is also a promising technique but its implementation at large scales will be hampered by the lack of adequate tools for monitoring plant water stress plus it implies a drastic switch in irrigation planning from the existing supply-oriented system to a more plant demand-oriented system. A case study in Tunisia showed that irrigating cereals at 70% of their actual water requirement levels resulted in only a very slight drop in yield. Despite these encouraging results, farmer's awareness raising and training sessions will be needed for this technique to be widely adopted.

Targeted research work in Morocco and Tunisia aims to promote the use of remote sensing observations to monitor plant demand and water stress. The added value of a decision support system designed to plan irrigation has been successfully demonstrated in real-life conditions at the plot scale (Le Page et al., 2014). One of the main limitations to its implementation at a larger scale (i.e. that of an irrigated perimeter) are the many existing constraints to on-time water delivery: the network of concrete channels extensively used for modern irrigation sectors, requires the sequential application of water to parcels; the channel flow is limited; the workforce is also a constraint. Recent preliminary simulation studies demonstrated that water saving could reach 25% even in a highly constrained irrigated perimeter, if information on actual plant water demand is taken into account in the irrigation planning strategy (Belaqziz et al. 2014).

Summary and conclusion

The executive summary of this chapter is as follows:

Global warming could increase freshwater water availability in spring during the transition period, and this should be taken into account in future watershed management policies. This could happen through increased snow melt and an already observed change in the rain/snow partition.

Long term monitoring of the water resource is of prime importance both for sustainable management and for model calibration. Given the weakness of existing *in situ* networks, remote sensing is an essential tool in these areas.

The groundwater depletion already observed in many southern Mediterranean catchments could negatively affect the poorest farming communities, who do not have financial means to deepen their wells.

Planning irrigation based on plant demand rather than the actual supply-oriented approach could enable substantial water savings even in the case of highly constrained existing modern irrigation systems.

Policies that promote water saving techniques including drip irrigation and deficit irrigation should be added to farmer training, control of water usage, and monitoring of agricultural intensification to fulfil the objective of saving water.

Foreseeing, monitoring and developing measures for adaptation to the expected changes requires an integrated catchment-wide approach to water management that brings together researchers and stakeholders. This requires building properly calibrated numerical modelling platforms, taking advantage of long-term observations including remote sensing data, to construct different scenarios of climate and anthropogenic changes (land use, irrigation methods, catchment planning) and their associated impact on water resources.

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Challenges for mitigating Mediterranean soil erosion under global change

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Introduction

Soil is an essential resource that provides a wide range of ecosystem services (Dominati et al. 2010). Its formation is slow, but its destruction can be rapid. Soil erosion by water is a natural phenomenon that is impacted by human activities and global change. The long history of intense cultivation and a unique combination of relief, parent material and climate conditions makes Mediterranean soils and soil patterns very different from those in other regions in the world. Several studies have shown that, in the Mediterranean basin, current soil loss rates drastically exceed soil formation rates (Kosmas et al. 1997). In addition, an increase in intense precipitation events due to climate change is expected in the 21st century. For these reasons, suitable adaptive managing strategies for Mediterranean soils cannot be simply transposed from experiments conducted in other regions of the world. This paper presents the main lessons to be drawn and challenges involved in preventing soil erosion in the Mediterranean region under global change reported in the literature, plus results obtained in several research projects[1].

Soil erosion in the Mediterranean basin

Mediterranean soils are particularly prone to erosion (García-Ruiz et al. 2013) because of (i) marked relief, 45% of the region has slopes greater than 8%, (ii) the high frequency of intense rainfall events (> 100 mm h^{-1}) in fall and winter, (iii) the presence of poor, shallow and skeletal soils, and (iv) sparse natural vegetation subjected to severe summer droughts. In addition to these natural drivers, intense cultivation even on steep slopes, burning, overgrazing and deforestation can greatly accelerate soil erosion, which, on the other hand, is limited by the many soil and water conservation measures (SWC) such as terracing in hilly areas.

The impacts of soil erosion can be divided into on-site and off-site effects. On-site effects are due to soil loss at field scale which, in certain extreme conditions, can lead to a net loss of cultivated area. This quantitative soil loss impacts agricultural production through the loss of nutrients, soil water reserves, and alterations to soil properties. Soil erosion also has significant off-site effects through the delivery of sediments to rivers, which affects the mobilization of water by siltation of reservoirs, and reduces the quality of water destined for irrigation and drinking.

Higher sediment yields (SY) than in many other regions have been measured in the Mediterranean basin (Woodward, 1995). These were often explained by the high contribution of gully and riverbank erosion processes (Vanmaercke et al. 2012). Gullies and especially badlands have been identified as a major source of sediments involved in siltation of reservoirs in the Mediterranean region (De Vente et al. 2006). The majority of SY occur during a few extreme rainfall events ("time compression", González-Hidalgo et al. 2007). However, these generalities mask huge variability across the basin as a whole. Based on a dataset containing 104 cumulated years of continuous SY measurements in eight small catchments ranging from 0.15 to 1.3 km^2 in size (Figure 1), Smetanova et al. (submitted) show that (i) the annual SY varied between 0 and ~27100 $t{\cdot}km^{-2}{\cdot}yr^{-1}$; (ii) catchments display two main contrasted patterns of SY seasonality; (iii) time compression is highly variable from one catchment to another. Ben Slimane et al. (2015) demonstrated that the predominance of gully and riverbank erosion processes in the Mediterranean basin was site dependent and not as widespread as previously thought.

1. http://www.agence-nationale-recherche.fr/?Projet=ANR-06-VULN-0012, http://www.obs-omere.org/, http://jeai-vecteur.org/, http://www.sicmed.net/#/projets-projects/3778554https://sites.google.com/site/rosmedsicmed/, http://jeai-vecteur.org/

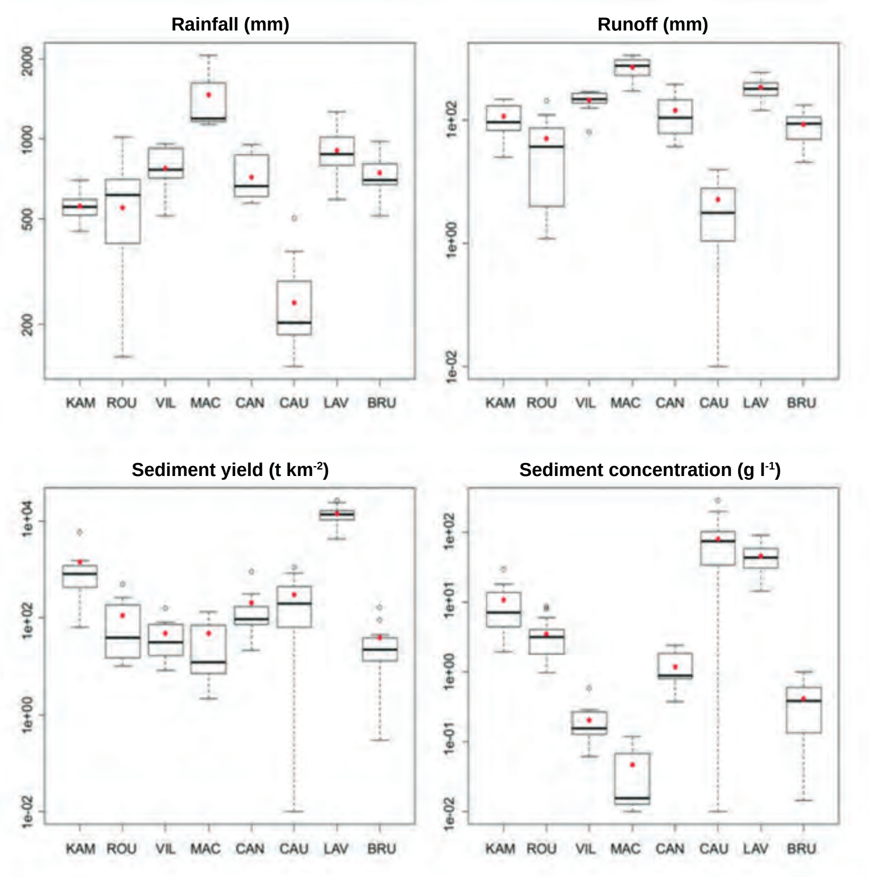

Figure 1
Range of intensity of erosion processes in the Mediterranean basin illustrated through inter-annual variability of rainfall (mm), runoff (mm), sediment yield (SY) ($t \cdot km^{-2}$) and sediment concentration ($g \cdot l^{-1}$) observed in 8 catchments of the R_Osmed network: KAM (Kamech, Tunisia), ROU (Roujan, France), VIL (Can Vila, Spain), MAC (Macieira de Alcôba, Portugal), CAN (Cannata, Italy), CAU (El Cautivo, Spain), LAV (Laval, France), BRU (Brusquet, Spain). Inter-annual means are plotted as red circles.

Expected future changes in Mediterranean soil resources under global change

Climate change will have both direct and indirect effects on soil erosion. Direct effects are due to changes in the amount, erosive power and spatio-temporal pattern of rainfall. Global change model projections indicate that longer droughts and more frequent extreme precipitation events are likely to occur.

Because of the high degree of SY time compression, the increased frequency and intensity of the largest events will increase soil erosion. The soil system reacts non-linearly to such changes, so even small increases in rainfall amount or intensity can dramatically increase soil loss rates. Climate change could also lead to a temporal shift in both the vegetation cover and the rainfall pattern that could positively or negatively indirectly affect erosion rates: the decline in surface runoff (which triggers erosion) could be partly counterbalanced by reduced biomass growth. Soil erosion could also be strongly affected by changes in land use and management due to human drivers (e.g., technological changes, demographic and socioeconomic trends and governance structures). Indeed, land use and management controls both soil characteristics and the distribution of overland flows. Some widespread crops, including vineyards and olive groves, and practices such as extensive overgrazing in mountain areas are known to encourage erosion. An increase in land abandonment and forest fires because of global change could also increase erosion in young fallows and post-fire conditions.

In the MESOEROS21[2] project, the impact of changes in rainfall characteristics and land cover on the risk of soil erosion in the Mediterranean basin was evaluated using a set of erosion models on (i) small and medium size gauged watersheds in France, Tunisia and Morocco, and (ii) the Mediterranean basin as a whole. The models were parameterized using measurements from highly gauged catchments and applied to the largest basins to calculate present and future conditions. Climate changes were estimated from global general circulation simulations and adapted to local conditions. Several land use change scenarios were built, including an «Accentuation » scenario in which both cultivated and natural vegetation are degraded, and a « Protection » scenario in which natural vegetation and good practices in cultivated area are favored. Two main results of the project (Paroissien et al. 2015; Simonneaux et al. 2015, Cerdan et al. 2011) were:

1) Simulating soil erosion rates is difficult because of the marked spatial and temporal variability of the processes involved and the uncertainty associated with the input parameters;

2) Land use is the main driver of changes in erosion risk and soil vulnerability in the Mediterranean basin.

2. Mediterranean Soils EROsion and vulnerability to global change during the 21st century

Main challenges for the future of Mediterranean soil resources

Toward a better knowledge of the factors and processes involved in soil erosion

Despite the increased availability of spatially distributed data, model application is still hampered by the low quality of input data. We therefore need to make better use of recent techniques to complete the too sparse legacy soil data to capture short scale soil variations in the Mediterranean basin and to improve our knowledge of future conditions to design efficient adaptation techniques. Long-term catchment erosion monitoring systems and Mediterranean networking initiatives are ideal ways to obtain a good picture of the variability of erosion processes and to explore the specific role of major/extreme events or sedimentological connectivity involved in sediment yield (SY) variability.

Toward the evaluation of soil risk

There is a need for a scientifically sound yet simple index of the risk of soil erosion that combines erosion rates and vulnerability and can be readily understood by decision makers. When assessing soil erosion vulnerability, it is important to consider the soil as a patrimonial resource that combines several basic soil functions (e.g., soil fertility and carbon storage) but also cultural and civilizational values related to religion, livelihood and health (Minami, 2009). The choice and valuation of criteria to be used for SE vulnerability are however complex issues, especially in the Mediterranean basin where for example, vineyards or olive trees can grow in soils that would be considered as very degraded using standard criteria. Even when the focus is on a very simple criterion such as soil depth as in Paroissien et al. (2015), soil vulnerability to erosion is difficult to estimate because soil depth is neither a standard, nor an easy, measurement.

Toward site specific conservation strategies

Mediterranean civilizations have successively developed or improved a wide range of techniques to improve water conservation and management, increase agricultural production, and reduce soil erosion. These techniques mainly concern correcting the slope/ reducing water velocity (e.g. through terraces), increasing ground cover (e.g. through the use of cover crops), restoring rangelands, and/or improving soil quality (e.g. through amendments). Recently SWC techniques have extended to sustainable land management or conservation agriculture that favor less soil disturbance, using crop residues as mulch, continuous ground cover, and crop rotations or associations. The efficiency of no-till conservation agriculture in increasing topsoil soil organic content and improve the soil water storage is widely recognised in the Mediterranean basin (Mrabet, 2011). However, these techniques

Box 1
Challenging issues for mitigating Mediterranean soil erosion under global change

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Raindrops control detachment directly through their impact on the soil matrix and indirectly through runoff, which is generally related to the decrease in infiltrability as a direct consequence of the degradation of the superficial structure under the action of rain (Moore and Singer, 1990). Rain also plays a role in particle transport: either in transport caused by the impact of drops, or in transport flow caused by raindrops (Kinnel, 2005). Looking at detachment by raindrops in more detail, it turns out that the rain actually controls two distinct successive processes: 1) the disintegration of particles at the surface and 2) the motion of the fragments produced by disaggregation by splash effect. Rain therefore plays an important role both in the total mass of eroded soil and in the size of the particles set in motion (Legout et al., 2005). Rainfall is usually directly measured by rain gauges but these only provide local and partial information for the scientific issues we want to address.

The first issue concerns the appropriate descriptors for rain (the diameter and number of drops, rain intensity and kinetic energy, and so on) that influence the erosion processes: they are not yet well defined and no consensus has yet been reached in the scientific community. It is consequently necessary to diversify measurements of rain to identify which factors concern erosion. A disdrometer is an instrument used to measure droplet size distributions and the values of other descriptors of rain. This instrument was used during laboratory experiments of detachment with rainfall simulators generating different intensities and energies. These experiments confirmed that the strongest kinetic energies were associated with the largest detached masses. It was also demonstrated that the strongest energies detached the largest proportions of fine particles (that are more easily mobilized by runoff). These observations were confirmed on 120 m² erosion plots under natural rainfall.

The second issue concerns the spatio-temporal structures of rainfall that lead to significant hydro-sedimentary responses. To address this issue, access to spatialized information with high temporal frequency is required. Although weather radar provides indirect measurements, it fulfils this requirement. It is a complementary observation tool that is all the more useful as Mediterranean rainfall can be very localized and last only a very short time (often a few minutes).

Several observation systems are available to deal with these issues including "ORE Draix" in the Southern Alps, "SNO OHMCV" in the Cevennes and "ORE OMERE" for Kamech watersheds in north eastern Tunisia. These observatories have hydro-sedimentary devices for the measurement of suspended sediments, sometimes sediment traps, and precipitation devices (rain gauges, disdrometers, sometimes radar) in various hydro-climatic and soil-use contexts.

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have varying degree of success depending on the environmental and societal contexts (García-Ruiz, 2013). Maintaining a continuous land cover may for instance have positive impacts on soil protection but negatives ones on production because of competition for water in semi-arid areas (Marques et al. 2010). In the end, the benefit of each technique needs to be checked in site-specific conditions, especially in Mediterranean areas where the complexity of the landscape results in significantly diverse contexts. Lessons from past changes in the Mediterranean environment through a review of adaptation techniques already experimented and a site by site evaluation of their soil protection efficiency and acceptability by local farmers will be helpful. Many mitigation strategies cited above are based on profound changes in agricultural practices. The massive introduction of such strategies in existing Mediterranean agrosystems is a challenge, and will have to take the specificities of each agrosystem into account, along with its socio-economic and environmental dimensions, and be supported by local or national policies.

Conclusions

Mediterranean soil resources are crucial for the social and economic development of the region but their sustainability is threatened by intense erosion processes, which have severe on-site and off-site effects. However, the nature and intensity of active erosion processes are as varied as the mosaic of Mediterranean landscapes. Realistic maps of soil erosion risk, vulnerability and sustainability cannot be produced without knowledge of erosion factors and processes acquired in awareness of this diversity.

When we modeled future soil degradation and catchment sediment delivery, the direct impacts of climate change alone were found to be lower than the impacts of changes in land use or in land management. The first challenge is thus to better forecast future changes in land use/management changes, whether or not driven by climate. The second challenge is to propose a strategy to anticipate projected changes and to mitigate their impacts. A wide range of adaptation or mitigation techniques exists and many have already been tested in the Mediterranean basin. It is now important to evaluate their efficiency and acceptability in the wide range of site-specific conditions. This will require new integrated approaches able to combine (i) quantitative and qualitative impacts of soil erosion; and (ii) natural and anthropogenic factors and processes.

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Inter-disciplinary post-event surveys to disentangle hazard from vulnerability in the impacts of Mediterranean flash-flood events

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A matter of space and time scales

Heavy precipitation events (HPE) and flash floods (FF) are common phenomena over the Mediterranean region. The peculiar topography and geographical location of this area make it especially favorable to the occurrence of intense events. The Mediterranean Sea acts as a vast heat and moisture reservoir from which baroclinic atmospheric systems pump part of their energy. The steep orography surrounding the Mediterranean Sea favors lifting of the low-level unstable air and initiation of condensation processes. Although they occur in well-known synoptic conditions, these intense rainfall events result from complex interactions between the atmosphere, the sea and continental surfaces. Mesoscale processes (orographic forcing, but also deflection and convergence of air masses, formation of cold pools and down-valley flows, etc.) lead to a variety of convective systems ranging from orographic rainfall events, thunderstorms, to the most dangerous stationary mesoscale convective systems (MCS) (Bresson et al. 2012). Despite recent progress due to the assimilation of mesoscale meteorological data in highly resolved numerical weather prediction models, the predictability of thunderstorms and MCSs remains quite low both in terms of intensity and localization.

Moreover, the morphology of the Mediterranean basin with its numerous small and steep river catchments and increasing urbanization of the coastal zones trigger very rapid hydrologic responses. The subsequent FFs are very dangerous for the exposed populations. A clear link exists between the hydrologic response (fig. 1) and the size of a watershed subject to a HPE. Typical times to peak can be as short as 10 min for urban watersheds of 10 km², and as short as 1-2 hours for natural basins extending from some tens to some hundreds of km² in mountainous settings. The time to peak spans a range of about one order of magnitude for a given watershed surface, showing that the hydrological responses also depend on other factors, such as topography, geology, land use, storm intensity and initial soil moisture. There is also a relationship between the space-time scales of the generating rainfall events (fig. 1) and the hydrologic response. This supports the concept of "scale resonance", e.g., a thunderstorm is likely to generate FF events over urban basins of some tens of km² while a stationary MCS is required to produce FFs and floods over watersheds of 100-2,000 km². Regional floods (e.g. Rhône River floods) are associated with frontal systems with much larger spatial extension and temporal duration.

Regarding the coping capacity of the exposed societies, the concept of "timeliness of flood anticipation" was proposed by Creutin et al. (2013) to describe how a sequence of anticipatory actions (known as the IOP sequence, for Information, Organization, Protection) is synchronized with the development of the flood. The situation is particularly tense in the Mediterranean context due to the limited predictability of rainfall and the rapid hydrological responses. Exposed individuals may experience a wide range of hazard conditions with different timeframes, depending on the size of the upstream watershed where they are located. The most critical situations are likely to occur at the finest spatial scales. Ruin et al. (2008) demonstrated that the majority of casualties that occurred during the 2002 Gard event in France happened in watersheds of less than 50 km².

As a detailed complement to the regional analyses proposed by Gaume et al. (2016) (subchapter 1.3.4), in the following sections we provide illustrative results obtained from inter-disciplinary post-event surveys (PES) aimed at understanding the complexity of both the hydrological responses to HPE and the behavior of the exposed populations during such sudden crises. So far research on

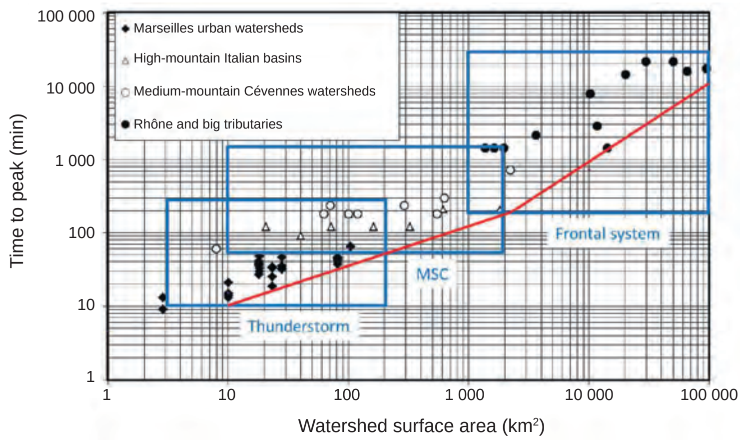

Figure 1

Hydrological response of Mediterranean and Alpine basins expressed in terms of the time to peak (delay between the hyetograph centroid and the flood peak) as a function of the surface area of the watershed. The red lines define the envelope curve of the shortest times to peak, critical information for warning and crisis management. The blue rectangles show typical space-time scales of the generating rain events.

hydrological and social systems has proceeded in "separate boxes" without many contacts between research disciplines (Parker et al. 2012). The consequence is that neither physical nor social sciences have acquired a comprehensive overview that would enable improvement of event response. We believe that the PES approach is needed to disentangle the respective contributions of hazard and human vulnerability to the impacts of flash-flood events, notably the causes and dynamics of casualties.

Complexity of the hydrologic response to extreme precipitation events

The recent development of weather radar networks opens new perspectives for the characterization of the space-time variability of the generating rainfall events. Weather radars provide rainfall estimates at appropriate resolutions, typically (1 km², 5 min). However, rain gauge data remain a critical source of information to constrain radar data processing algorithms and/or to validate the radar estimations. Bouilloud et al. (2010) proposed a pragmatic method for dealing with two main physical errors of radar, namely those due to the interactions between radar waves and the relief and those due to the vertical structure of the rain systems. Geostatistical methods proved to be optimal for merging corrected radar data and rain gauge data (Delrieu et al. 2014) by removing the bias of radar estimates while retaining their enhanced perception of the spatial variability of rainfall.

Hydrological PESs aim to collect three types of data (Gaume and Borga 2008; Marchi et al. 2009):

(i) Peak discharge estimates over ungauged upstream basins; this is done by performing cross section surveys (cross section and energy slope estimation using flood marks) complemented by clues concerning flow velocities (e.g., video recordings, water super-elevations in front of obstacles, etc.).

(ii) Indicators of the time sequence of the flood (time of peak(s), dynamics of the flood rise and recession). For ungauged sections, this information is obtained from eyewitness accounts.

(iii) Indicators of sediment transfer processes (erosion and deposition in the river beds, mud or debris flows) as an indication of the runoff processes, flow energy and velocity. This is particularly relevant in high mountain settings (Borga et al. 2014; Rinaldi et al. 2016) where such processes create specific risks and affect both the landscapes (soil conservation) and the rivers (channel instability, reservoir filling, etc.).

Figure 2 illustrates the results of the PES conducted after the disastrous flood event that affected the Gard region on September 8-9, 2002 (Delrieu et al. 2005; Bonnifait et al. 2009). This disaster (24 casualties, 1.2 billion euros) was due to an MCS system that remained stationary for 28 hours and produced more than 200 mm rain over an area of 5,500 km², and which locally reached more than 700 mm. The green insert in figure 2 shows the added value obtained from the PES in terms of documenting the peak discharges for ungauged basins (< 100 km²). The specific peak discharges reached extreme values (40 $m^3s^{-1}km^{-2}$) at the smallest spatial scales investigated (1-10 km²). The blue insert gives three examples of rainfall-runoff time series for upstream ungauged watersheds. The hydrographs were produced with a hydrological model constrained by the estimated PES discharges and checked with the reconstructed time sequences obtained from the PES. Note that different rainfall-runoff scenarios can be observed locally with single and double peak discharges, fully explained by the displacement of the MCS during the event. At the outlet of one of the main rivers (red insert), the distributed hydrological model was too reactive; coupling with a 1D hydraulic model was necessary to represent the control exerted by the Gardon Gorges. The latter resulted in major flooding of the upstream plain, thereby protecting the city of Remoulins from an even more disastrous flood, an interesting example of geomorphological control on medium-scale flood. The hydraulic model also showed that the operational rating curve of the gauging station available prior to the event largely overestimated the discharges, an example of the marked uncertainties affecting flood discharges even in gauged stations. Other factors that determine the hydrological response are the initial soil moisture status and the geology (Vannier et al. 2016). Frequently advocated factors such as deforestation, poor river bed maintenance and even urbanization are likely to play a marginal role in the case of heavy rainfall events when the storage capacity of the soils is fully saturated.

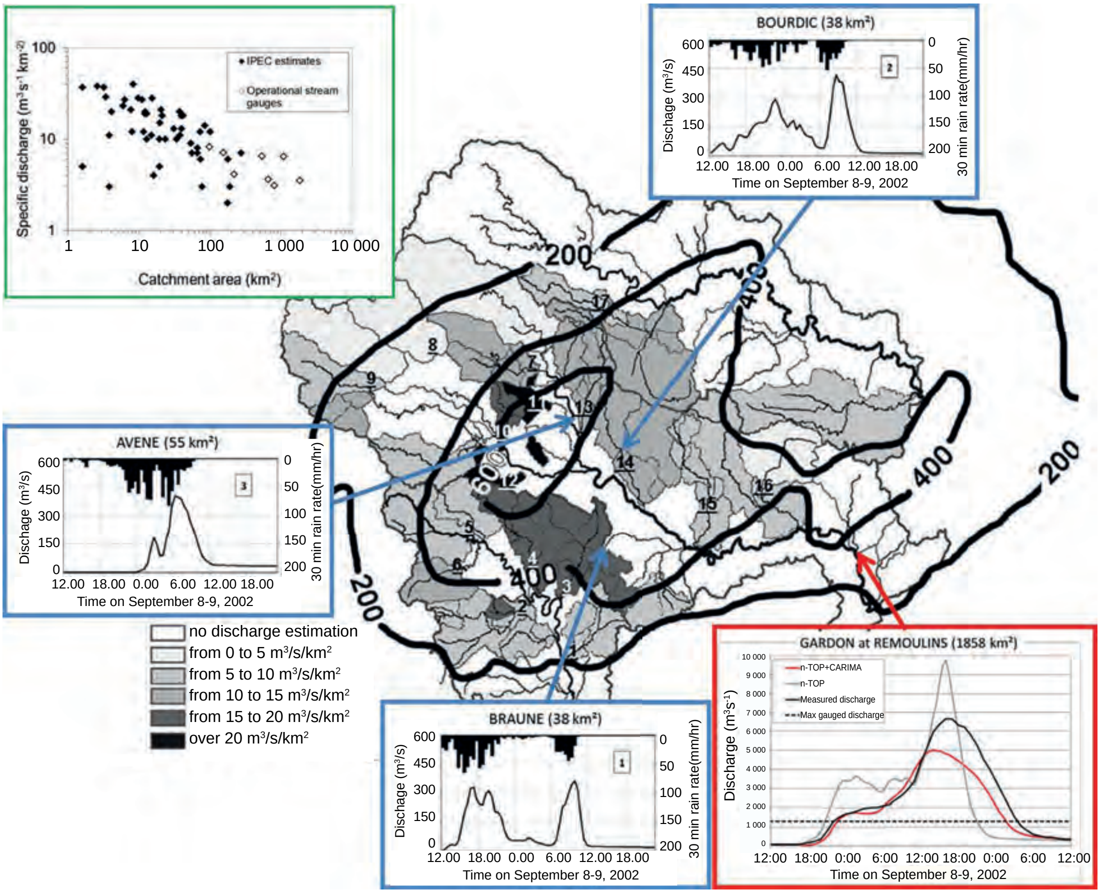

Figure 2

Illustration of the hydrological response complexity of the Gard event in France on September 8-9, 2002. The map shows the rainfall isohyets (contours of 200, 400, and 600 mm of rain) superimposed on the river network of the affected area. The sub-watersheds are colored as a function of the maximum specific discharges estimated during the PES. The green insert shows the maximum specific discharges estimated during the PES for ungauged catchments as well as those derived from operational gauging stations as a function of the surface area of the watershed. The blue inserts give 3 examples of the response of small upstream watersheds. The red insert shows the hydrologic/hydraulic response at the outlet of the Gardon watershed at Remoulins.

How do individuals cope with flash floods?

The social PES aims to collect behavioral, temporal and spatial information related to changes in the environmental conditions and activities in which people are involved prior to and during the crisis. Its objective is to document how individuals switch from routine activities to emergency coping behaviors. It is structured around a chronological guideline with which interviewees are invited to recall what they perceived from their environment, what actions they undertook, and with whom they interacted in different places and while moving in between places. The survey campaign starts by interviewing the contact people identified during the hydrological PES. These people are also asked to recruit other interviewees with whom they were directly or indirectly in contact at various stages of the event. This snowball sampling technique makes it possible to collect diversified and complementary information.

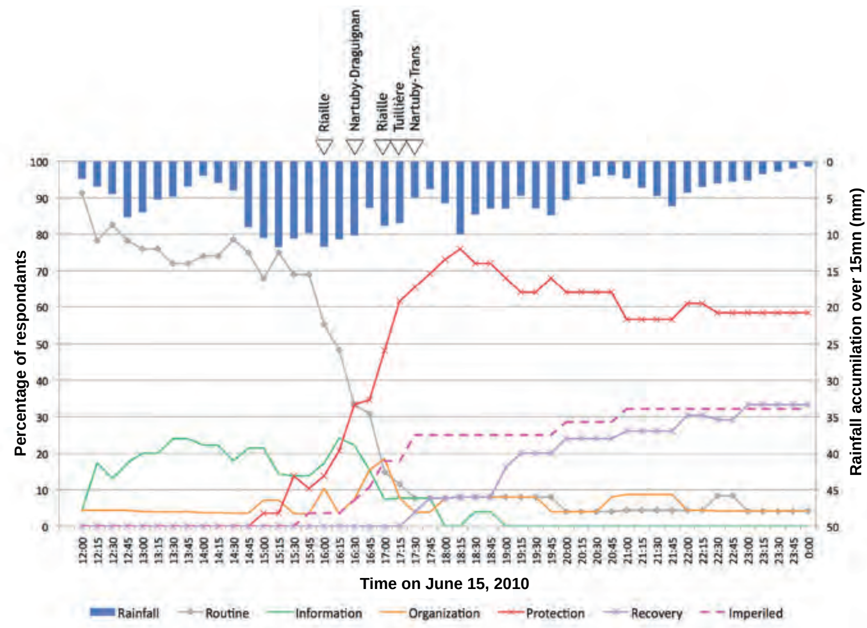

Figure 3
Changes in behavioral responses of the social PES respondents during the FF event on June 15, 2010 in Draguignan, France, in terms of routine activity, awareness of the crisis through information, organization, protection and recovery actions. The cumulative percentage of imperiled people during the event is also shown. Note the rapid drop in routine, information, and organization curves to the profit of the protection curve between 15:30 and 17:30 which corresponds to the danger outburst (peak flows, generalized surface runoff). The orange vigilance warning launched by Météo France the preceding day and the TV news at midday reached only a limited proportion of respondents (20%).

This approach was first used after the June 15, 2010 FF event in the Var region, France (Ruin et al. 2014) which was responsible for the deaths of 26 people. Data collection efforts concentrated on three municipalities located on the Nartuby River. Figure 3 shows the proportion of interviewees as a function of the type of activity over time, together with rainfall intensity and the times of peak flood in the corresponding watersheds.

This social PES allowed us to identify some possible causes of the individual responses. The possible conflicts of priority between routine and exceptional circumstances explained the difficulty in switching from daily activities to responding to warnings. The difficulty in making sense of environmental cues in the case of insufficient official warning also emerged as a possible cause of delay in individual responses. Because FF environmental conditions vary tremendously across space in very short periods of time, it is often difficult for those who are affected to fully grasp the situation in which they find themselves or to imagine the variability of the threat moving across space. The study also revealed a form of the individual's self-organization and the emergence of helpful social interactions that may involve different types of social ties. Finally, this case study confirmed the role of contextual factors (Parker et al. 2009): the timing of the hydro-meteorological event, its severity, and experience of the flood appear to be essential in the ability of individuals to make sense of the situation and to adapt their activities.

Conclusions

As a complement to regional analyses (Gaume et al. 2016, sub-chapter 1.3.4), we believe such inter-disciplinary post-event surveys are indispensable for the mitigation of FF events in the Mediterranean because they allow a better understanding of the causative hydrological processes and the subsequent social responses in different climatological and social contexts around the Mediterranean Sea. Due to their heavy death toll, so far, the focus has been on short-term crisis management with the aim of increasing people's preparedness through education, and improving the efficiency of warning and alert systems. Obviously, long-term management of this type of natural hazard also involves socio-economic considerations related to land planning and controlled urbanization, a particularly difficult topic in the context of the increasing human pressure and the expected climate change in the Mediterranean region.

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Sub-chapter 2.3.5

Changes in Mediterranean groundwater resources

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Introduction

The strong variability in space and time of all components of the hydrological cycle is a fundamental feature of the Mediterranean region (e.g. Cudennec et al. 2007). Its most visible marker is the succession of droughts and floods that deeply affects environment and societies. Impacts of such events on groundwater are obvious but there are countless drivers of hydrological changes that act under multiple forms.

Among them, irrigation is of primary importance. For millennia, Mediterranean populations developed strategies of adaptation to water scarcity and exploited groundwater to secure crops against seasonal and interannual irregularity in rainfall and river flows. Ancient Mediterranean civilizations have left many traces of their hydraulic mastery from the tapping and transfer of spring water to the drainage of aquifers or the digging of deep wells (e.g. Remini et al. 2010).

But the 20th century represented a complete disruption because technical advances allowed massive access to groundwater. Irrigation now represents between 50% and 90% of the total Mediterranean water demand (UNEP/MAP-Plan Bleu 2009) and has based its "silent revolution" on intense groundwater exploitation. This has led to critical drops of groundwater levels of up to several hundred meters in a few decades (e.g. Custodio et al. 2016). Many other human interventions have consequences for groundwater quantity and quality including changes in land use and land cover, hydraulic works, artificial inflows and outflows. These often interact at different scales of time and space, which makes the current state of groundwater a complex combination of multiple processes.

Original features of groundwater resources

Sedimentary aquifers are by far the largest regional reservoirs in the Mediterranean region. Most are small or medium in size, i.e. a few hundreds or thousands of square kilometers. They represent the last stage of an eventful geological history that still influences the present, especially active tectonics and variations in sea level since the Miocene. The apparent opposition in water circulation processes between fissured carbonates and porous media often plays a secondary role in comparison with more important properties like storage capacity and resilience to external stresses.

The first driver of their recharge is the heterogeneous distribution of rainfall, which is largely influenced by topography, particularly apparent by the contrast between relatively humid hinterlands and drier littorals. Recharge depends mainly on the intensity and distribution of rainfall events in space and time, and on vegetation and soil surface conditions: monthly and annual amounts of rainfall are only insignificantly linked with the real recharge reaching aquifers. The role of water towers played by upstream areas is illustrated by the Haouz plain of Marrakech whose groundwater originates from upstream catchments and not from direct infiltration of rainfall over the plain (Boukhari et al. 2015). The weakness or even complete lack of diffuse recharge and the major role of focused recharge are very common in the Mediterranean region.

Groundwater also comes from exchanges with rivers, especially during the highest floods. Depending on the event, infiltration can vary by one or two orders of magnitude. This implies that aquifer dynamics has to be analyzed simultaneously at several scales, from the event up to the millennium: the largest confined aquifer systems contain information dating back to the last humid period in the Holocene (e.g. Zuppi and Sacchi 2004).

Because of climatic surface conditions, a regional geology rich in carbonates and evaporites, and easy contact between the sea and the littoral aquifers, Mediterranean groundwaters are often highly mineralized. For instance, only one fifth of Tunisian groundwaters have a salt content lower than 1.5 $g.L^{-1}$ while another fifth exceed 4 $g.L^{-1}$ (Besbes et al. 2014). A significant proportion of the theoretically available Mediterranean groundwater resource is in fact not exploitable for human use without treatment.

Climatic change and groundwater

Apart from the few last centuries when direct observations have been made, climatic variations are reconstituted from proxies. As humans have been highly active in the Mediterranean for millennia, it is necessary to disentangle the climatic and human origins of apparent modifications of the socio-environments in the Holocene, and also to differentiate local and regional phenomena. Temperature reconstructions in the north-western part of the Mediterranean region by Camuffo et al. (2010) indicates that past cycles already reached current measurements. The resulting sea level rise is a potential threat for littoral aquifers, but far behind the threat represented by their modern exploitation. Regarding past variations in rainfall, the wide range of proposals in the scientific literature mirrors the wide range of data, methods and objectives of the authors concerned. According to careful analyses (e.g. Reiser and Kutiel 2011) no coherent regional trend can be identified over the 20th century. At a longer perspective of several centuries, some consistencies and also significant discrepancies appear in climatic reconstructions between eastern and western sub-basins or even between north-western and south-western sub-basins.

In recent decades or centuries, spectacular events that may have marked infiltration are attributable to the usual great variability of the Mediterranean climate. And today, the multiple forms of anthropization of the hydrological cycle completely dwarf the climatic signal.

Anthropization of groundwater resources

Expansion of irrigation highly exploits groundwater resources whatever their renewal rate. Cases of severe overexploitation are numerous and widespread throughout the region: in Libya, the demand for water for irrigation is about ten times higher than renewable water resources. Even worse, overexploitation in fragile aquifers leads to rapid social and environmental disasters like in the coastal Chaouia of Morocco (Moustadraf et al. 2008). But cases also exist where the development of irrigation leads to an increase in the superficial groundwater resource because of a significant return flow of excess irrigation water, pumped from deeper aquifers or imported by large channels, like in the Spanish Cartagena aquifer (e.g. Baudron et al. 2014) or the Moroccan Tadla aquifer (e.g. Bouchaou et al. 2009).

Changes in water consumption for irrigation are far more influenced by technical (e.g. drip systems), economic (e.g. energy cost), social (e.g. local knowledge) and political (e.g. subsidies) drivers than by increasing temperatures modifying crop water demand. There is evidence for a wide range of illicit but tolerated groundwater exploitation practices in many Mediterranean countries, which are sometimes even encouraged by national authorities. Two emblematic cases are widespread unauthorized boreholes and unauthorized plants for desalinating brackish groundwater.

Apart from irrigation, agriculture modifies land uses and land covers in many ways (areas covered by rangelands, forests and fields; crop intensification; etc.) that modify the proportion of blue and green water, and consequently the flux and location of groundwater recharge.

Hydraulic works are another major component of the modification of the groundwater regime, either by a direct impact or by an intermediate effect on surface water that subsequently modifies recharge. Hydraulic works include a very wide range of sizes and construction modes from big and small dams to soil and water conservation works, and traditional bench terraces. Their number considerably increased in the 20th century, and only a very few of them were built with the explicit intent of modifying recharge (e.g. Martin-Rosales et al. 2007), probably less than cases of unexpected losses that contribute significantly to new groundwater inflows (e.g. Leduc et al. 2007). The efficiency of the recharge of these different hydraulic works varies considerably over time, depending on siltation, maintenance, etc. This non-exhaustive list can be completed with pumping and refuse from quarries and mines, losses of long distance water transfer, drainage of wetlands, plots for artificial recharge, etc.

Groundwater is also intensely exploited for the supply of drinking water, which has rapidly increased as a consequence of population growth, the improved ratio of the population supplied, and higher standards of living. The concentration of population in Mediterranean coastal areas results in an ever increasing demand for drinking water in areas where groundwater of good quality is often naturally rare and sources of quality degradation numerous (e.g. seawater intrusion, waste water). To the fundamental priority of drinking water is added the provision of groundwater for tourism and industry, which are usually present in the same areas as cities and increase the spatial and temporal disequilibrium of groundwater exploitation.

Consequences of changes for groundwater

Anthropization of the Mediterranean environment directly affects the location, temporality and intensity of groundwater fluxes in both recharge and outflow (e.g. limitation of floods in alluvial plains, increased vertical fluxes under irrigated schemes, leakage inversion). It also affects groundwater quality, in nearly all cases leading to its degradation: increased mineralization of water stored for a longer time at the surface before infiltration (e.g. in irrigated fields, in dam reservoirs), pollution by fertilizers and pesticides used in agriculture, advance of seawater intrusion, uncontrolled discharge of wastewater, artificial mixing of groundwaters in defective or multiscreened boreholes, etc. The qualitative consequences of groundwater anthropization are often less perceptible (i.e. less visible and/or less surveyed) than drops in groundwater level, which partly explains the inertia of decision makers before implementing costly remediation actions that have to be continued over long periods.

The progressive superseding of natural processes by anthropized ones increases the complexity of both hydrodynamics and geochemistry, at multiple scales of space and time (Fig.1). The consequence should be a supplementary effort to densify survey and analysis whereas in practice, most observation networks have worsened under financial constraints in the last two decades. Some are no longer appropriate for the new emerging issues, and large territories remain almost unknown.

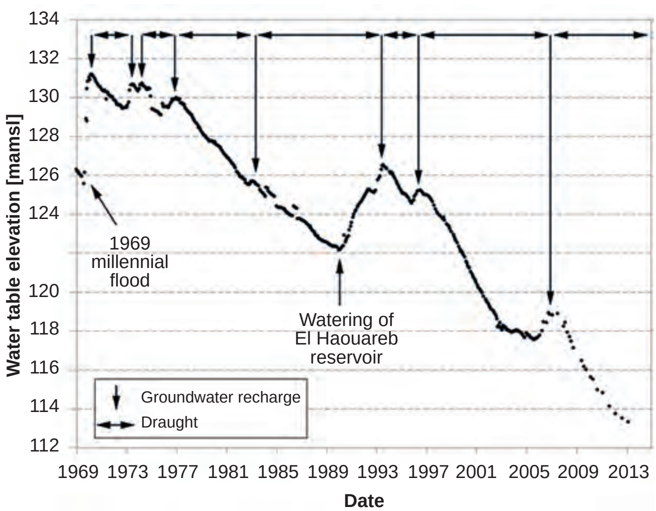

Figure 1
Changes in the water table depth in the Kairouan plain. The two biggest rises are due to the catastrophic floods in 1969 and the construction of the big El Haouareb dam; other rises due to wet years are much smaller. But the major trend is the severe long term drop caused by the ever increasing pumping for agriculture.

The capacity of water managers to inform their decisions with groundwater knowledge diminishes with time, in parallel with the higher pressure on groundwater resources, the higher vulnerability of socio-hydrosystems, and the much stronger claim of citizens to play an active role in the decision process. In addition to individual requests, collective welfare and long-term sustainability must also be taken into consideration. This is particularly important for environmental water demand, often taken as an adjustment variable, and sacrificed to needs that are considered to be more urgent, at the risk of causing irremediable damage. This addresses the more general issue of the role of states and their ability to enforce law.

The rapid evolution of Mediterranean socio-environments is a major challenge for scientists and managers. The intricacy of technical, societal and biophysical drivers is progressively increasing and taking new forms. Among these multiple drivers, climate change currently has less impact than many other drivers. Whatever their relative importance in the future, beyond traditional disciplinary and/or technical studies, holistic approaches will have to be developed, and anticipating major crises will largely depend on our ability to imagine possible futures outside traditional thought frameworks. Most Mediterranean groundwater resources have been considerably reduced in quantity and degraded in quality in recent decades, preserving their resilience capacity is an absolute necessity to withstand the projected increase in the frequency of extreme events.

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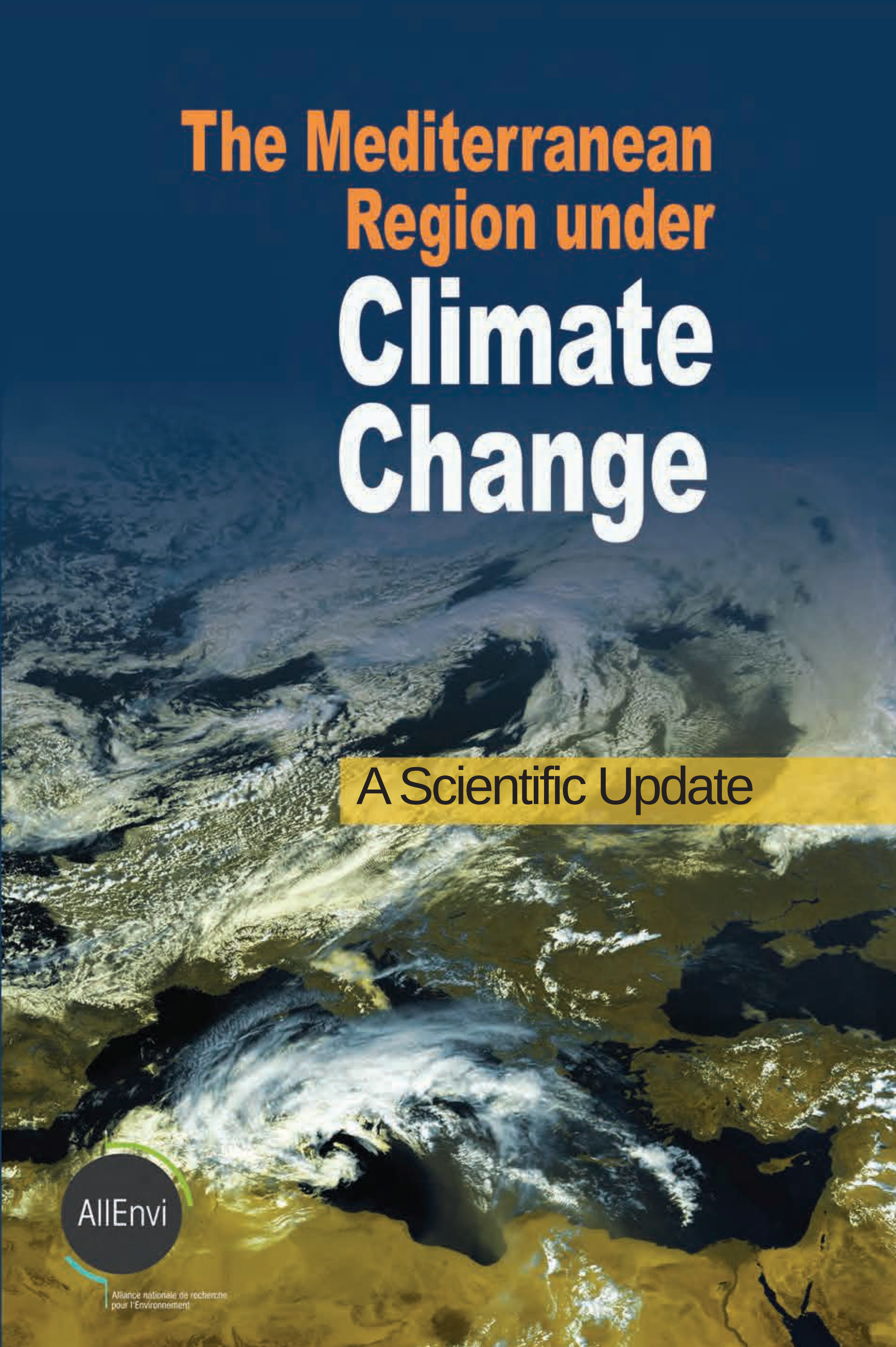
The Mediterranean Region under Climate Change

A Scientific Update



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A Scientific Update

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