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Scarcity and multiple stressors in the Mediterranean water resources: The SCARCE and GLOBAQUA research projects

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Summary. The Mediterranean basin is one of the regions of the world most vulnerable to global change and one of the "hot spots" for predicted problems in water availability. Current climate change models forecast that the Mediterranean region will register increased summer drought and stronger rainfall events. Since freshwater ecosystems deliver important services to society, water scarcity affects both ecosystems and humans. Within this context, two different research projects have assembled a multidisciplinary team of leading scientists in the fields of hydrology, chemistry, ecology, ecotoxicology, economy, sociology, engineering, and modeling to study the interaction of multiple stressors with respect to pressure on water resources. SCARCE (2009-2014), with the full title of "Assessing and predicting effects on water quantity and quality in Iberian Rivers caused by global change," focuses on the Mediterranean river basins of the Iberian Peninsula. GLOBAQUA (2014-2019), with the full title "Managing the effects of multiple stressors on aquatic ecosystems under water scarcity," expands the area of concern to several Mediterranean basins in Europe. Both research projects link basic research aspects with management practices and policy implications in a single framework. SCARCE is funded by the Spanish Ministry of Economy and Competitiveness through the Consolider-Ingenio 2010 program (CSD2009-00065), whereas GLOBAQUA has the financial support of the European Communities 7th Framework Programme, under Grant Agreement No. 603629-ENV-2013-6.2.1-Globaqua. [**Contrib Sci** 10:193-205 (2014)]

Introduction

Water is the most essential of all natural resources. Water and water-related services are major components of human well-being and critical factors in the socio-economic development of Europe. Nowadays, freshwater ecosystems are under threat due to a great variety of stressors with potentially deleterious effects, including organic and inorganic pollution,

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geomorphological alterations, land cover change, water abstraction, invasive species and pathogens, and water scarcity [32]. Most of our current knowledge is based on the effects of single stressors on chemical and ecological status [19] and ecosystem functionality. However, this has limited our capacity to understand ecosystem responses to multiple stressors.

Water scarcity is defined as a structural, persistent drought affecting resources and aquatic ecosystems, with implications for water quality and societal needs. It occurs when water demand exceeds water resources exploitable under sustainable conditions [27]. It can be a stressor on its own because of its structural nature but it can also drive the effects of other stressors, for example, increasing the concentrations of pollutants in rivers because of the constant input of pollution in the setting of decreasing water availability [25]. Water scarcity is therefore a key stressor because of its direct and indirect effects in terms of the chemical and ecological status of water, but also in terms of sustaining of ecosystem services [14].

Water scarcity is one of the main problems faced by many societies in the 21st century. Water use has been growing at more than twice the rate of population increase in the last century, while resources are dwindling or, at most, have remained constant. Although water scarcity is an integral part of the Mediterranean environment, exponential demographic growth, climate change, and pollution together threaten the delicate balance established over many years. In the Mediterranean, as a semi-arid region marked by highly variable river flows, including the occurrence of low flows, water scarcity is a natural condition. In addition, the Mediterranean basin is one of the world's most sensitive areas regarding the possible consequences of climate change [4] and one of the most impacted regions because of human demand for water. Climate change places further pressure on the region's water resources, with rising temperatures, more frequent droughts, unpredictable rainfall patterns, and higher flood frequency [16]. Despite the uncertainties involved in these projections, it is highly probable that water availability will be reduced in Mediterranean areas as a consequence of increased temperatures and decreased and more variable precipitation [6]. These alterations probably will not be limited to the Mediterranean region itself but also to all areas of the world with a Mediterranean-type climate. An additional concern besides the consequences of global warming is the overexploitation of water resources in arid and semiarid regions. While the percentage of water consumption with respect to total available resources is only 7.4% in the northern Iberian Peninsula, which is characterized by an Atlantic climate, it is as high 55% and, according to some estimates, even 224% in Mediterranean basins. Some climatic and hydrological models predict that the percentage of areas in Europe with serious water stress could increase from the current 19% to 34–36% in 2070 [28]. Hydrological models also indicate a shared responsibility among the effects due to climate change and those that are directly related to the anthropogenic overexploitation of natural resources, with implications for future resource availability.

Although it is the consequences of water scarcity that affect human interests that largely motivate our concern, water scarcity also has implications on hydrological resources and systems connectivity, as well as negative side-effects on biodiversity, water quality, and river ecosystem functioning. The temporal interruption of water flow is common in Mediterranean rivers but scarcity causes an increase in the frequency and length of these episodes, which in turn increases the natural effects of water intermittence such that ecosystem resistance capacity is overwhelmed. The chemical quality of water will be affected, as higher nutrient and pollutant concentrations are expected under lower water flows. The discharge of point sources of contamination into rivers without the necessary dilution provokes both an increase in the contaminants and a decrease in dissolved oxygen. The effects of water scarcity on drainage networks range from hydrological irregularities to variations in geomorphological dynamics (higher channel incision, habitat simplification). Biological communities respond to harsher environmental conditions with lower diversity, the arrival of invasive species, and a lower efficiency of biological processes (nutrient uptake, primary production, decomposition, etc.). The delivery of ecosystem services to society, as described in the Millennium Ecosystem Assessment [21], may be affected by effects of water scarcity on ecosystem functioning. Services such as the improvement of water quality, the provisioning of water for drinking or irrigation purposes, and protection against floods become endangered. In summary, water scarcity is not only a simple matter of available resources to fulfill human needs. Rather, the good quality of natural systems is also essential to guaranteeing their viability and functioning. Ignoring this aspect threatens not only their existence but also the quality of the services they are expected to deliver.

With rapid population growth, environmental degradation, and climate change, it is no longer possible to satisfy water demand solely by increasing the supply, which was the traditional water policy response in the Mediterranean. Today, water supply-and-demand management requires limiting losses and inappropriate use while ensuring more efficient use. This involves a shift in attitude for decision-makers, who for decades have sought to increase supplies through the construction of dams and by large-scale well-drilling. These actions reflect the incomplete information relied upon by water authorities to implement long-term strategies aimed at mitigating the deleterious effects of global change. They are also the consequence of gaps in our knowledge on effects of multiple stressors, especially within the frame of increasing water scarcity [5,26]. To properly address the effect of stressors in policy terms, a coordinated research effort that considers multiple perspectives is needed. A range of national and EU-funded research projects and policies such as the EU Water Framework Directive (WFD) are directly or indirectly supporting water- and climate-related actions.

Two projects initiated as part of this effort assembled multidisciplinary teams of scientists in the fields of hydrology, chemistry, ecology, ecotoxicology, economy, sociology, engineering and modeling to carry out the research necessary to understand the interactions of multiple stressors in exerting strong pressures on water resources. The aim of both projects is to improve current management practices and policies by identifying the main drawbacks and alternatives (Fig. 1). The SCARCE project focused on the Mediterranean river basins of the Iberian Peninsula while the GLOBAQUA project, which can be considered as a follow up project, targets several Mediterranean basins of various European countries. Both projects, SCARCE and GLOBAQUA, are coordinated by one of our institutes, the Water and Soil Quality Research Group of the Institute of Environmental Assessment and Water Research of the Spanish Council for Scientific Research of Barcelona (IDAEA-CSIC).

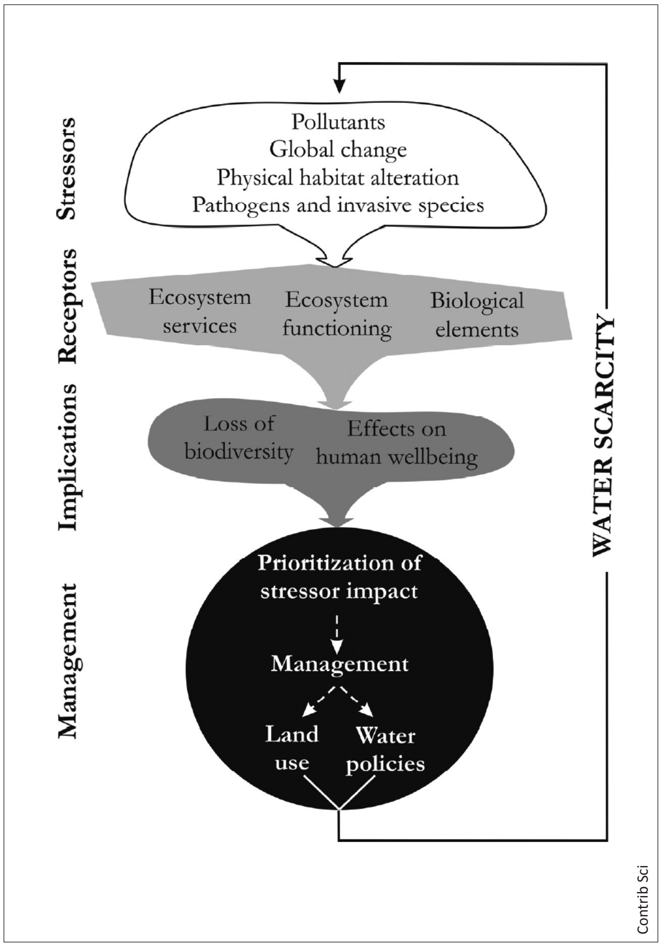

Fig. 1. Conceptual links considered in the projects.

The SCARCE project

As one of the Consolider-Ingenio 2010 projects (Spanish Ministry of Economy and Competitiveness), SCARCE, with the full title "Assessing and predicting effects on water quantity and quality in Iberian Rivers caused by global change," was a 5-year project that was initiated in December 2009. A consortium was assembled, consisting of a multidisciplinary team from 11 partner Spanish institutions and the active involvement of water authorities, river basin managers, and other relevant agents as stakeholders. Scientific management of the project was tasked to the IDAEA-CSIC. The various disciplines contributing to the project ranged from hydrology, geomorphology, ecology, chemistry, and ecotoxicology to engineering, modeling, and economics.

SCARCE had two complementary objectives: (i) to tackle basic research questions in order to define the long-term patterns and mechanisms that operate in hydrology, sedimentary processes, water quality, habitat dynamics, and the ecosystem structure and functioning of Mediterranean basins and (ii) to determine the effects of climate and the human footprint on the ecosystem services of selected river basins, in recognition of the urgent need to implement and eventually redefine the River Basin Management Plans as mandated by the WFD. Therefore, SCARCE emphasized linking basic research and management practices within a single framework [22].

SCARCE structure. SCARCE was structured across 10 thematic Work Packages (WPs) that coordinate the various scientific goals (Fig. 2). The WPs dealed with data collection (WP DATA), hydrology (WP HYDROL), sediment transport and river channel morphology (WP MORPH), chemical and biological quality (WP QUALITY), ecosystem processes (WP PRO-

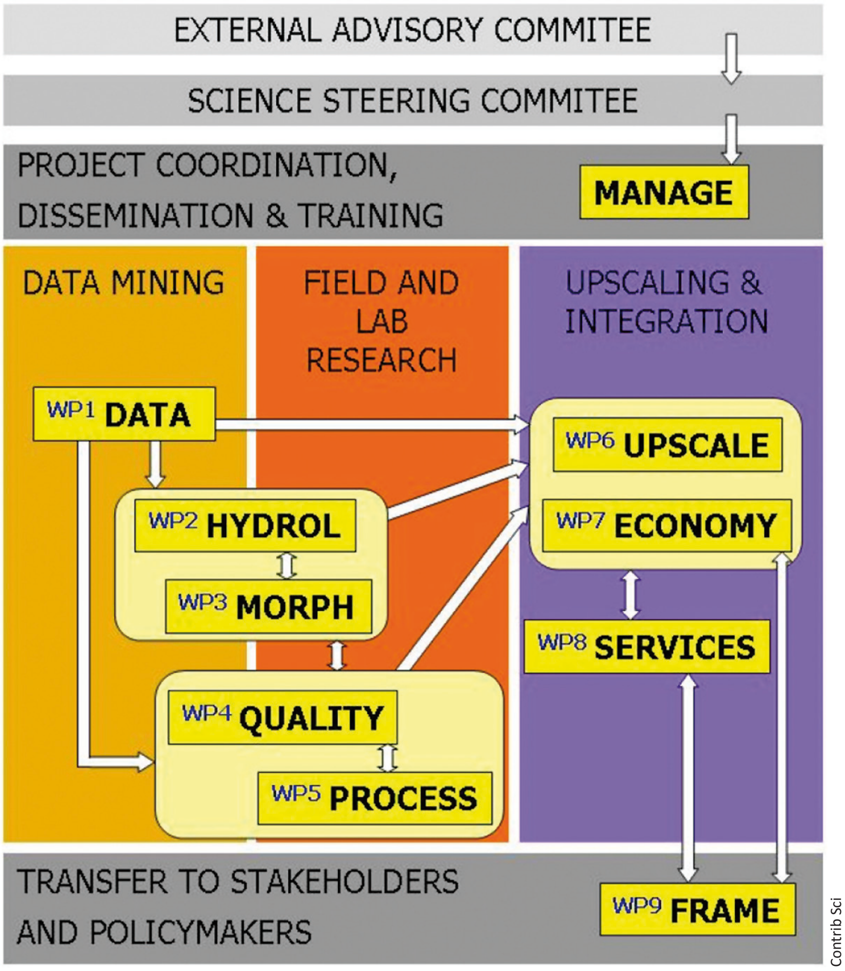

Fig. 2. SCARCE project structure and interaction between WPs.

CESS), modeling (WP UPSCALE), socio-economic scenarios (WP ECONOMY), ecosystem services (WP SERVICES), river management (WP FRAME), and coordination (WP MANAGE). All of these could be classified under one or more of the three defined main topics (Data Mining, Field and Lab Research, and Upscaling and Integration). The exceptions were WP MANAGE, which dealed with project coordination, dissemination, and training activities, and WP FRAME, whose main objective was the transfer of all the findings to the stakeholders and policy-makers for their future application in the management of river basins. The Science Steering Committee coordinated and monitored the progress of the work carried out in each research line and the External Advisory Committee ensures the social and political feasibility of the proposed management methods.

SCARCE worked on four different spatial scales: microscale, mesoscale, water body, and catchment. The work in each WP took place at one or several of these scales. WPs collecting new data (HYDROL, MORPH, QUALITY, and PROCESS) mostly operated at micro and mesoscales (from m^2 to km^2). The analyses carried out by the other WPs (UPSCALE, ECONOMY, SERVICES, and FRAME) examined responses at higher scales. SCARCE applied a multidisciplinary cross-scale approach combining data mining with field-based research in several representative basins in Spain.

Study basins. Three representative basins in the Mediterranean Iberian Peninsula region, where water scarcity is the main problem, and one Atlantic Iberian Peninsula basin included in the Mediterranean climate region have been selected to obtain a complete Mediterranean perspective and an expanded vision of the implications of water scarcity in the Iberian Peninsula. The selected basins were the Ebro, Llobregat, Jucar, and Guadalquivir (Fig. 3). They were selected for their characteristics but also considering their previous inclusion in other European and national projects, which increased the amount of data available and allowed a better and more detailed study of river processes.

In these four basins, several studies have taken place in order to answer the integrated questions that have been put forward in SCARCE. Based on the use of both surface and groundwater resources, the selected basins encompass a rich set of socio-ecological conditions (forested mountainous areas, highly populated watersheds relying on water transfers, agricultural areas, and industrial clusters) and a complete geographic coverage, thus allowing an evaluation of the Iberian situation with respect to the combined effects of multiple stressors on ecosystems and humans. The wide coverage of Mediterranean characteristics in the four basins will facilitate the transfer of knowledge generated in the project to all Mediterranean basins.

The Ebro River basin is the largest Mediterranean Spanish basin. It was chosen because of its highly variable hydrology, with high peaks but also water scarcity, depending on the season. It has a complex hydrological regime, as it receives water from tributaries under contrasting climates, ranging from snow-fed Pyrenean rivers to more typical Mediterranean tributaries in the southern part of the basin. Most of the Ebro basin is agricultural land, making it one of the most irrigated areas in Spain; lately, however, increasing industrial and urban pressures have come from five main industrial cities [7,23]. It is an appropriate site for carrying out specific and controlled experiments as extensive data are already available from river basin authorities, who are open to collaborating with the project.

By contrast, the Llobregat is a small basin, but with a larger population than the Ebro basin. Consequently, it is under heavy anthropogenic pressure and receives extensive urban and industrial wastewater discharges as well as surface runoff from agricultural areas that cannot be diluted by its natural flow. From the hydrological point of view, this is a typical Mediterranean river: its flow is highly variable as a result of seasonal differences in rainfall. Periodic floods and droughts lead to frequent morphological variations in the river bed. The river is heavily managed in its lower course, and water that once ran to the sea is now pumped upstream to increase natural flow, recharge the delta wetlands, and control seawater intrusion. It is thus an illustrative example of an over-exploited river [11].

With a similar, typically Mediterranean hydrology, the Ju-

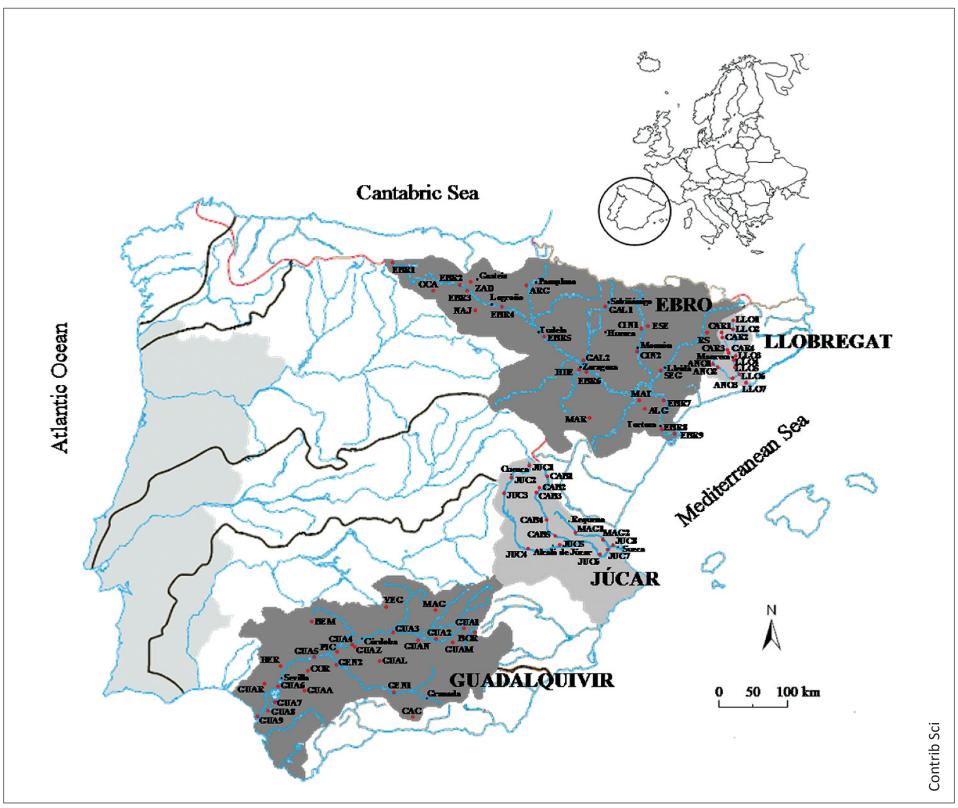

Fig. 3. The four river basins studied in SCARCE and the selected monitoring sites.

car is also a small basin in which agriculture accounts for nearly 80% of water demand (1,394 $Hm^3 y^{-1}$ for 200,000 Ha of irrigated crops). However, whereas agricultural demand appears to have stabilized or is decreasing, urban/industrial demand is forecasted to rise [9,24]. The human population living in the basin (over 1 million people) makes intensive use of the available water, with demand often exceeding supply [9].

Finally, the Guadalquivir is a large basin with a Mediterranean climate but in its lowest part it is also influenced by the Atlantic Ocean. More than 7 million people live in the basin, 60% of them in cities; 30% of urban and industrial sewage is poured untreated into the Guadalquivir [20]. More than 700,000 Ha of the basin are devoted to agriculture, especially the production of rice, olives, and fruits. The river is navigable as far as Seville (a major inland port about 90 km upriver), resulting in serious erosion and pollution problems. The Guadalquivir basin is one of the most diverse in Europe, as it harbors almost half of the plant species on the continent and most of those in the North African region.

An extensive network of 77 sampling sites has been established in the four selected river basins and two extensive monitoring campaigns have taken place, the first one in October 2010, during a period of high flow, and the second one in October 2011, when flow was low-medium. These sampling sites covered the most highly impacted areas and were therefore appropriate for chemical, hydrological, morphological, and ecological analyses. They also included reference sites in river sections where the water quality was expected to be high. All the WP field studies that have been performed consider all or some of these sampling sites. The basic research element of the field-based study was the kilometer-scale river reach, including the river channel, the alluvial plain, and associated groundwater, as well as the river reaches downstream from dams. At this scale, the impacts of global change on several processes affecting freshwater ecosystem services could be evaluated: nutrient processing and contaminant retention, sediment transport, community assembling, and habitat integrity, etc. Different mathematical models were then used to scale up the results from the river basins studied to the whole Mediterranean region in Spain. Information from the project was regularly updated and available at the SCARCE Website [http://www.scarceconsolider.es].

Work undertaken. Under WP DATA, contacts with water agencies have been established and data have been collected in all the basins, pre-processed, and compiled in a common database. This database also comprised all data generated in the project thus far, mainly related to the field work completed in 2010 and 2011. The collected data included water quality (both chemical and biological parameters), hydrology (long data-series across the basins), and cartographic information (land uses, impacts, and flooding areas). The data series from water authorities have been assessed to determine ecotoxicologial risks due to global change [18]. Several climatic change scenarios (meteorological and hydrological) have already been analyzed, processed, and used in different studies [25]. Flagship sites have been determined for use in calibrating the models.

WP HYDROL dealed with processes taking place at a small to medium scale. The emphasis thus far has been on hydro- as well as geo-chemical characterizations in saturated soils/sediments, with the aim of evaluating the fate of contaminants (both inorganic and organic). Laboratory experiments in tanks were conducted to characterize the amount of mixing, and consequently the interactions, caused by temporal variations in water flow. A number of batch tests have been carried out under controlled batch conditions to determine whether different micropollutants are degraded under certain redox conditions [3]. Finally, a probabilistic approach to evaluate the potential risk of hydrological practices related to water supply systems based on the use of fault trees has been devised. The proposed methodology allowed the integrated inclusion of the uncertainty coming from very different fields (hydrology, chemistry, biology, medicine, social sciences, and economics) [8]. The consequences of the artificial recharging of aquifers in a site located at the Llobregat River basin (batch test and field applications) have been studied, as well as the time dependent interaction between hydrogeological and health components in health risk predictions [17].

WP MORPH has undertaken an extensive field campaign to characterize key hydraulic, sedimentary, and vegetation parameters at the 77 selected sites along the four representative basins. The data have been used to derive information on the active and full channel and on associated flow depth and shear stress, by means of hydraulic modeling. Long-term changes in river morphology were assessed by analyzing available air-photos series. As a second step, seven sites (the Esera, Isabena, Algars, Ribera Salada, and Cabriel rivers) have been selected for the analysis of morphosedimentary dynamics and sediment transport and for the construction of hydraulic, sediment transport, and habitat models. These sites were labeled as *reference* and *modified* and were representative of climate and degree of flow regulation in each of the basins. Impacts on channel and riparian corridor have been assessed during field surveys, including impacts on longitudinal and lateral connectivity (e.g., dams, dykes, riprap, weirs, culverts, and other man-made structures) [30], artificial changes in the channel platform, and adjustments of the river bed (i.e., degradation/aggradation) [31].

Within WP4 QUALITY, two extensive sampling campaigns (low-medium and high flow) have been undertaken. A total of 77 samples of water, 75 sediments, and 63 pools of fish were collected for chemical characterization together with water and sludge from 13 wastewater treatment plants (WWTPs). The levels of over 250 compounds, priority (polycylic aromatic hydrocarbons, organochlorine pesticides, and alkylphenols) and emerging contaminants (pharmaceuticals, drugs of abuse, personal care products, polar pesticides, perfluorinated compounds, endocrine disrupting compounds, halogenated flame retardants, and nanoparticles), have been determined using validated established advanced analytical techniques and newly developed methods based on gas chromatography-tandem mass spectrometry and liquid chromatography-tandem and hybrid mass spectrometry [12,15]. The invertebrate community has been sampled in each basin along a toxicity gradient. The habitat (fine sediment) and sites were the same as those sampled in the chemical characterization, which allowed the identification of potential relationships between the concentrations of the various compounds and the organisms. The parameters analyzed in the invertebrate community were: density, biomass, species composition, and biochemical markers (lipid concentrations and oxidative enzymes). Estimations of environmental risk in the studied basins for invertebrates have been obtained using historical data (obtained from water agencies) on priority compounds and biological indexes [13].

WP PROCESS has followed a twofold approach. First, in an attempt to gather summary data on river ecosystem processes across multiple sites, experiments on the decomposition of organic matter (poplar tongue depressors) have been performed at all 77 reaches included in the project. The results have been analyzed by multivariate statistics to discern the main environmental factors governing the spatial patterns of wood breakdown in wet years [1]. Second, experiments addressing the effects of: (a) irrigation on litter breakdown, (b) dams on nutrient dynamics and river metabolism, and (c) WWTP effluents on river ecosystem functioning have been conducted. Advances have been made in conceptualizing a mechanistic model of river ecosystem functioning.

WP UPSCALE implemented external models of dynamic vegetation and inorganic nitrogen, yielding TETIS-SCARCE [10]. A new, user-friendly interface and new abilities of the model have also been developed. The rainfall-runoff model TETIS has been calibrated and validated in the basins of the Júcar, Siurana, Ésera, and Llobregat rivers, with satisfactory results obtained for calibration and validation processes. A new aspect was the modeling of the emerging pollutant diclofenac using the GREAT-ER model for the Llobregat River basin. Bed-load transport models in a large regulated gravel bed river (lower Ebro River) have been evaluated as well. Finally, the Aquatool DSS-Júcar has been calibrated and validated for the quantity and quality modules (SIMGES and GESCAL, respectively). For the Aquatool DSS-Llobregat, the aim was the development and calibration of detailed water quality models and determinations of salt balances in the zones of influence of the salt mines in the Llobregat and Cardener rivers. Initial simulations have focused on the water quality in drought episodes and validation of the models for the period 2007–2011.

WP ECONOMY focused on the social and economic effects induced by the alteration of ecosystems, as a consequence of global and climate change processes. In close relationship with other WPs, its tasks were based on the ecosystem services approach. To assess the current contribution of aquatic ecosystems to society and to anticipate possible alteration due to climate change, five case studies have been established (Anoia, Arga, Noguera de Tor, Júcar, and Guadalquivir) to achieve a socioeconomic appraisal of ecosystem services. Field trips, the development of deliberative scenarios with respect to ecosystem services, and the creation of a questionnaire on social perception have been completed. Preliminary results confirm the usefulness of an ecosystem services approach in addressing the complex relationships between society and ecosystems. The research carried out thus far can be considered as a solid first step in future refinements and extensions of the ecosystem services approach, especially in relation to the application of models carried out by the WP SERVICES.

WP SERVICES has implemented the InVEST model in the Llobregat basin, which was selected as a pilot basin to adapt the model to Mediterranean conditions, with the aim of assessing the impact of climate change on the delivery of key hydrological ecosystem services. One example was estimation of the service "water provisioning." This service has been calculated using the terrestrial module InVEST, with the main considerations being precipitation, evapotranspiration, and human demand [2]. Accordingly, water provisioning, waste treatment, and sediment retention services were selected among the whole set of considered services to be used in the developing phase of the model. This model was also developed for the Ebro River basin; other ecosystem services, such as erosion control and water purification, were included. A non-monetary valuation technique has been implemented in the Ebro basin for the service water provisioning. The supply-to-demand ratio has been used as a metric to assign value to this service and to characterize the effects of management scale, climate extremes, and potential mitigation measures on water scarcity issues along the basin [29]. Two different exercises on the effects of climate extremes and climate change have been performed at the Llobregat basin: the first on the effects of climate extremes (dryer and wetter years of the series 1960–2010), and the second on the effects of climate change conditions (scenarios of the A2 and B1 climate change models).

WP FRAME has developed several activities related to the communication of achievements of the project to river-basin management authorities and end-users. A large number of researchers, end-users, stakeholders, and management authorities participated in the kick-off meeting of the project and in the subsequent international conferences that have been organized once a year within the framework of SCARCE. There has been a high level of interest for the objectives of the project and significant feedback for updating research needs at the basin level. Collaborations between members of SCARCE and the water/agencies authorities have continued during the 5 years of the project. Thus, a number of meetings have been held with several water agencies and water authorities of the basins to inform them about developments useful for their management activities. These meetings were requested after a preliminary informative meeting with river managers and officials from the Spanish Ministry of Agriculture, Food and Environment. A survey has been submitted to management authorities, policy-makers, stakeholders, and end-users to identify the knowledge that is necessary to generate new scientific management tools. Thus far, four special issues containing papers from the first to fourth International Conferences have been already published in *Environmental Science and Pollution Research* (Environ Sci Pollut R 19:915-1042). *Science of the Total Environment* (Sci Total Environ 440:1-320; Sci Total Environ 503-504:1-328) and *Journal of Hazardous Materials* (J Hazard Mater 263:1-265). A fifth one, with papers from the final SCARCE International Conference, is in *Science of the Total Environment*.

The GLOBAQUA project

As one of the last FP7 projects (European Commission), GLOBAQUA is a 5-year project (February 2014–January 2019) and a follow up of the SCARCE project. The consortium is composed of 22 European partners from eight countries (including one SME) and two non-EU partners from Morocco and Canada. The institutional experience of the consortium covers a broad range of disciplines: chemistry, biology, ecology, geomorphology, hydrology, economics and sociology, including hydrological, biophysical, and ecological modeling, socio-economics and governance science, knowledge brokerage, and policy advocacy. Scientific management of the project is carried out by IDAEA-CSIC. The GLOBAQUA team includes practitioners and policy-makers (Stakeholder Panel) who will ensure that the project is highly relevant to the needs of end-users. By bringing together researchers with strong international experience and end-users with key expertise in the region, a critical mass of experience and knowledge will be mobilized to carry out project activities. The partnership is a result of the cooperation of several initiatives, existing networks, and research projects.

GLOBAQUA has two major complementary objectives. The first deals with fundamental research questions: improvement of our knowledge of the relationships between multiple stressors, identifying potentially synergistic linkages, and assessing how these interactions might determine changes in the chemical and ecological status. Special attention will be paid to the role of water scarcity as a central stressor and to the relationships between biota (different level of biological organization) and stressors. This envisages a holistic approach ranging from assessments of the effects on water quality, organisms, and ecosystems to those on socio-economical regional development. A broader aim is to establish cause-effect relationships between multiple levels using integrative modeling. The second objective addresses the urgent need to improve water management practice and policies by taking into consideration the influence of multiple stressors. This aspect is relevant to the WFD (2000/60/EC) and other related regulations. The objective will be achieved by analyzing current policies as well as scenarios of alternative management practices and policies [22b].

GLOBAQUA structure. To answer the integrated questions posed within GLOBAQUA, a cross-scale approach will be applied in several representative basins. The basic research element will be the kilometer-scale river reach, including the river channel, the alluvial plain, and associated groundwater. GLOBAQUA relies on a strong interdisciplinary team to facilitate knowledge transfer between researchers and stakeholders. The project is organized into 14 highly integrated WPs grouped in five main *Modules* (Fig. 4):

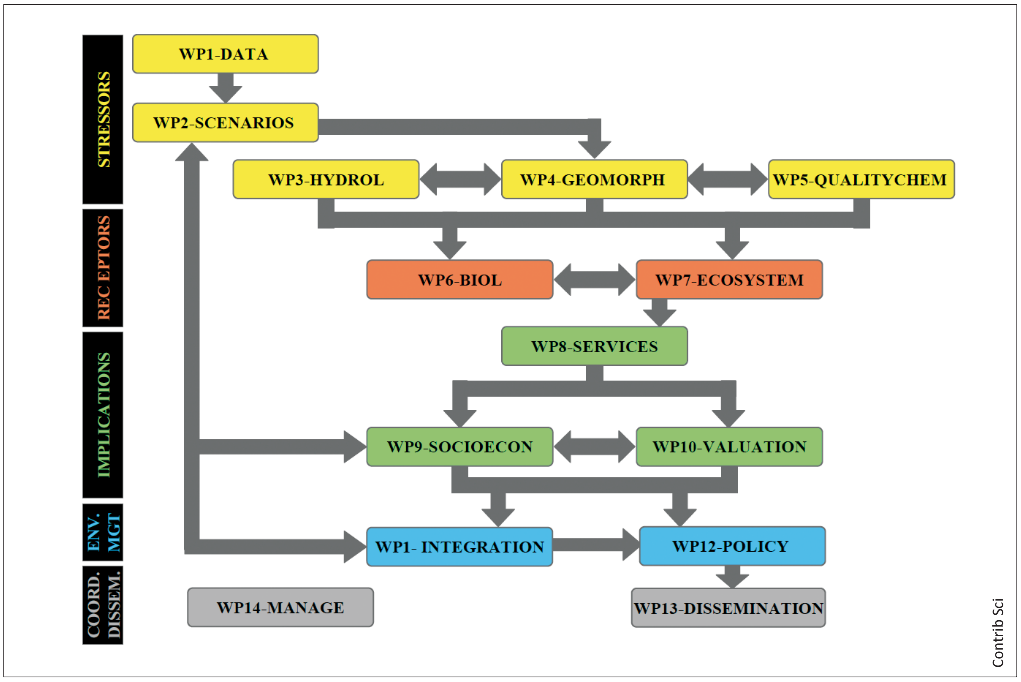

Fig. 4. GLOBAQUA project structure and interaction between WPs.

Module STRESSORS. The goal is to understand the mechanisms behind the multiple stressors acting in each case study: WP1-DATA will collect existing data from basin authorities and previous research projects and gather experimental data generated within the project. WP2-SCENARIOS will generate climatic, socioeconomic, and land-use scenarios to provide drivers for impact modeling. Its results will set the boundary conditions for the subsequent modeling WPs. WP3-HYDROL, WP4-GEOMORPH, and WP5-QUALITYCHEM will analyze surface and groundwater hydrological patterns, sediment and pollutant transport, and the quality of the physical habitat and the fate of inorganic and organic pollutants, respectively.

Module RECEPTORS. The effects of the stressors on biodiversity (WP6-BIOL) and ecosystem functioning (WP7-ECOSYSTEM) will be analyzed. Research will be based on manipulative laboratory experiments using artificial streams, reach-scale measurements, and basin-scale surveys, with the aim of understanding the effects of single and multiple stressors at different scales and to establish models dealing with the data at either the reach or basin scale. Results at the lab and reach scales will be used to feed mechanistic models at the reach scale, whereas basin-scale results will be used in statistical integrative models at the basin scale.

Module IMPLICATIONS. WP8-SERVICES will integrate the information generated by WP6-BIOL and WP7-ECOSYSTEM on the effects of stressors on receptors (biodiversity and ecosystem functioning) into integrative models at the reach or basin scales. These models will therefore relate changes in stressors to changes in diversity and ecosystem functioning and, in turn, with ecosystem services in biophysical terms. WP9-SOCIOECON will characterize the socioeconomic setting of the case-study basins to support the ecosystem services valuation performed by WP10-VALUATION. Finally, the impact of the changes in ecosystem services in economic terms on socioeconomic development will be assessed by WP10-VALUATION. This will help to identify the environmentally and socioeconomically sustainable management of water resources.

Module ENVIRONMENTAL MANAGEMENT. Two WPs will deal with relevant issues associated with the impact of multiple stressors on water quality, quantity, and ecosystems, as well as on the potential implementation of the major findings on European policy. Therefore, WP11-INTEGRATION will develop a model framework to assess scenarios affecting the availability, quality, and demand of water at the European scale. This WP will integrate the most relevant results of the previous WPs in other modules to define a manageable perspective on the multi-stressor consequences for European river basins. The implications of the stressors interactions and the opportunities for related policy-making will be analyzed by WP12-POLICY. Therefore, this WP is defined as the interface between the scientific results obtained all along the project and policy definition and development.

Module PROJECT COORDINATION AND DISSEMINATION. These WPs (WP13-DISSEMINATION and WP14-MANAGE) will run for the entire duration of the project to guarantee: (i) communication of the results to specific target groups (researchers, policy-makers, water managers, land planners, etc.) and stimulation of their use through relations with stakeholders and end-users, training programs for different end-users, and screening of IPR potential, and (ii) efficient coordination of all activities, day-to-day technical management, overall financial and administrative management of the GLOBAQUA consortium, and cooperation with stakeholder and scientific panels.

Study basins. Three representative basins from the Mediterranean European region, where water scarcity is the main problem, as well as one Southern Mediterranean basin (North Africa), have been selected to obtain a complete Mediterranean perspective and an expanded vision of the water scarcity implications. To achieve a full European dimension, one Alpine and one UK river basin, where scarcity is a growing issue, also have been included among the case studies. Based on the use of both surface and groundwater resources, the six selected basins encompass a rich set of socio-ecological conditions (forested mountainous areas, highly populated watersheds relying on water transfers, agricultural areas, and industrial clusters) and complete geographic coverage. Their analysis will provide important information on the combined effects of multiple stressors on ecosystems and humans in Europe.

The effects of multiple stressors on water availability and quality and on the chemical and ecological status of water will be examined, and the existing dysfunctions identified. A specific set of stressors will be targeted at each basin to illustrate different management scenarios. The selected river basins for GLOBAQUA are: Ebro (Spain), Sava (Slovenia, Croatia, Bosnia and Herzegovina and Serbia), Evrotas (Greece), Souss Massa (Morocco), Anglian (UK) and Adige (Italy) (Fig. 5). In four of them (Adige, Sava, Ebro, and Evrotas), extensive field work will be done to collect information on different stressors (pollution, pathogens, invasive species, geomorphological and flow regime alterations), while in two of them (Anglian river basin district and Souss Massa) the existing data will be used to evaluate different management scenarios.

The selection of the Ebro River basin as a focus of study was discussed in the section on the SCARCE project. A similar case is Sava, the largest tributary of the Danube. It was chosen due to the strong collaboration among all the countries included in its basin and because it is a cross-border river. Although the pressures are similar to those on the Ebro, the hydrology is less variable such that the influence of climate can be studied by comparing these two basins. Unlike these basins, the Evrotas (one of the major rivers of the Peloponnese) was chosen as a river that flows free without dams and almost no industrial pressure. Nonetheless, it suffers from water abstraction due to agricultural practices and the extremely dry climate, which causes desiccation in some areas. In contrast to the Ebro and Sava rivers, the amount of preexisting data is very small. A similar basin is Souss Massa, in which socioeconomic studies rather than fieldwork will be carried out to obtain the perspective of a non European Mediterranean basin. The other basin in which similar studies will be carried out is the Anglian, which belongs to the driest part of the UK and will add the perspective of a non Mediterranean river to the project. Finally, the Adige (Italy) has been added to extend the climatic conditions to mountainous ones characterized by glacier melting and pressures related to tourism and to hydropower production.

The case study work will start with the collection of existing data to understand the relation between stressors and biological status. The most appropriate river reaches will be identified with respect to data gaps, water scarcity, main stressors, and/or specific ecosystem services to society. Specific controlled field experiments will be performed to fulfill the specific objectives previously outlined. For instance, the interaction between chemical and physical stressors will be assessed by gathering information under different hydrological conditions (high and low flows) from the different receptors in river segments downstream of the discharge of WWTPs. Other specific controlled field experiments will be defined to assess the interaction between physical and chemical stressors and their effects on different receptors in river segments downstream from reservoirs and downstream from WWTPs. General information from the case-study basins will be gathered by means of simultaneous field sampling campaigns that include the Modules STRESSORS and RECEPTORS, thus guaranteeing the integration of methods and approaches. Joint field exercises will be organized to obtain quality data for the analysis of potential and real relationships between stressors and responses at the species and ecosystem levels. This information will be used to generate consistent scenarios for ecosystem goods and services, socioeconomic and environmental changes, and to assist in policy-making. The sharing of experiences and results between the case

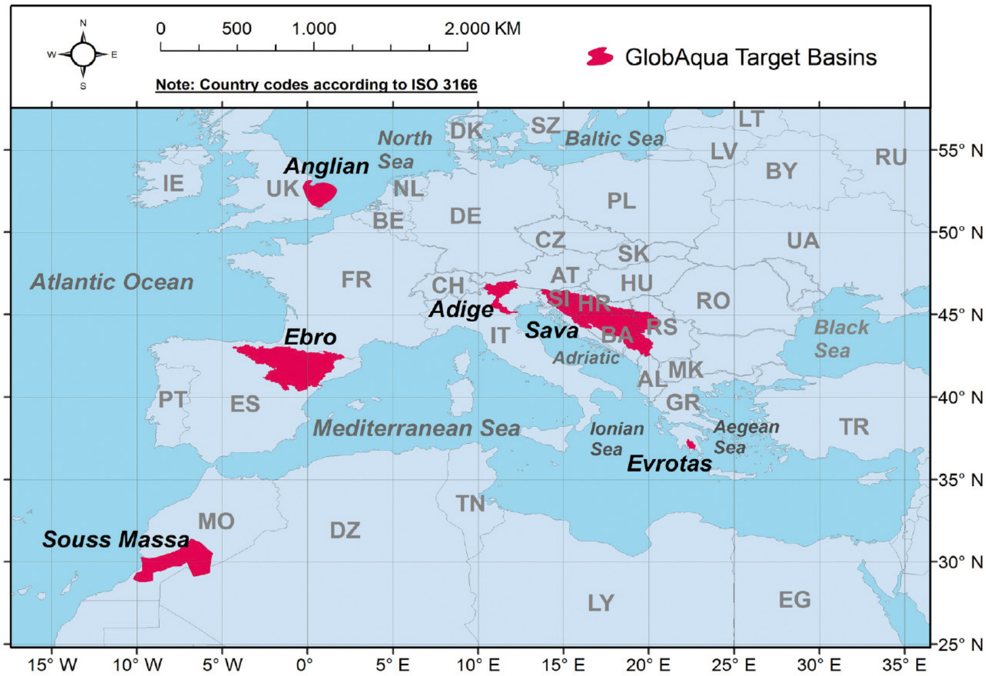

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Fig. 5. The six basins studied in GLOBAQUA.

studies and regular dialogue with stakeholders, through workshops and other meetings, will facilitate comparisons between case studies. The impacts of multiple stressors on several processes affecting freshwater ecosystems, their functioning and uses (e.g., flood mitigation, habitat integrity, sediment transport, community assembling, nutrient processing, and contaminant depletion capability) will be evaluated. Field research will consider: (i) hydrological episodes relevant to the project, such as seasonal droughts or flash floods, and (ii) sensitive areas affected by multiple stressors. Every site study will serve as a landmark in issues related to multiple stressors at a European scale (pollution, susceptibility to climate change, invasive species, etc.).

Final remarks

The SCARCE and GLOBAQUA projects are fully complementary in their aim of addressing the fundamental need to link the multiple stressors giving rise to water scarcity with the implementation of the appropriate policies in European river basins. They bring together a large group of researchers, stakeholders, and policy-makers across a wide range of disciplines. This challenge is met by communication tools including an Internet Platform for data exchange but also many scientific meetings among the various groups. The structure of the projects into WPs allows the sharing of responsibilities between researchers who are specialists in their respective fields. The work performed by the different WPs takes place at different scales. The achievement of an overall good status of European water bodies until 2015 (according to the WFD timetable demands) poses a crucial challenge not only to water management agents but also to policy-makers, the scientific community, and society in general. Management approaches to tackle EU water challenges will only work in the framework of cross-border actions integrating all relevant stakeholders and by making use of cutting-edge scientific knowledge. SCARCE has started to establish the necessary links between science and the operational policy- and decision-makers and actively involves authorities, agents, and (public) water suppliers as well as relevant stakeholders on a Spanish regional scale. This scale will be extended at the European level with GLOBAQUA.

Both projects develop proposals for cost-effective programs of measures (PoM) dedicated to case studies of river basins. Since the selected basins are representative watersheds in water-stressed areas in Europe and cover a wide range of socio-ecological conditions, the projects results and PoM will be adaptable and transferable to other European river basins and other areas (South Mediterranean). They will therefore contribute to achieving an optimal approach to challenges in water management.

The added value of this collaboration lies in the possibility of addressing the problems arising from water scarcity and multiple stressors/pressures and their effects on ecosystem services, and from the overall effects of global change. Taking into account the interaction between all main environmental compartments and processes involved, a complete picture of the situation will be obtained, with possible solutions visualized at different levels. Other benefits are mutual enrichment and methodological knowledge transfer. Overall, the synergy of the different groups arises from their different areas of expertise, which together provide a holistic picture of the problem, as well as potential solutions.

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References

1. Aristi I, Díez JR, Larrañaga A, Navarro-Ortega A, Barceló D, Elosegi A (2012) Assessing the effects of multiple stressors on the functioning of Mediterranean rivers using poplar wood breakdown. Sci Total Environ 440:272-279 doi:10.1016/j.scitotenv.2012.06.040
2. Bangash RF, Passuello A, Sánchez-Canales M, Terrado M, López A, Elorza FJ, Ziv G, Acuña V, Schuhmacher M (2013) Ecosystem services in Mediterranean river basin: Climate change impact on water provisioning and erosion control. Sci Total Environ 458-460:246-255 doi:10.1016/j.scitotenv.2013.04.025
3. Barbieri M, Carrera J, Ayora C, Sánchez-Vila X, Licha T, Nödler K, Osorio V, Pérez S, Köck-Schulmeyer M, López de Alda M, Barceló D (2012) Formation of diclofenac and sulfamethoxazole reversible transformation products in aquifer material under denitrifying conditions: Batch experiments. Sci Total Environ 426:256-263 doi:10.1016/j.scitotenv.2012.02.058
4. Barceló D, Sabater S (2010) Water quality and assessment under scarcity: Prospects and challenges in Mediterranean watersheds. J Hydrol 383:1-4 doi:10.1016/j.jhydrol.2010.01.010
5. Baron JS, Poff NL, Angermeier PL, Dahm CN, Gleick PH, Hairston NG Jr., Jackson RB, Johnston CA, Richter BG, Steinman AD (2002) Meeting ecological and societal needs for freshwater. Ecol Appl 12:1247-1260
6. Calbó J (2010) Water scarcity in the Mediterranean. In: Sabater S, Barceló D (eds) The Handbook of Environmental Chemistry. Springer-Verlag, Berlin doi:10.1007/978-3-642-03971-3
7. CHE (2008) “Confederación Hidrográfica del Ebro.” Accessed January 29 [Online] Available at: http://www.chebro.es
8. de Barros FPJ, Bolster D, Sánchez-Vila X, Nowak W (2011) A divide and conquer approach to cope with uncertainty, human health risk and decision making in contaminant hydrology. Water Res Res 47:W05508 doi:10.1029/2010WR009954
9. Estrela T, Fidalgo A, Fullana J, Maestu J, Pérez-Martín MA, Pujante AM (2004) Júcar Pilot River Basin, Provisional Article 5 Report Pursuant to the Water Framework Directive. Valencia (Spain), Confederación Hidrográfica del Júcar:208
10. García-Arias A, Francés F, Martínez-Capel F, Garófano-Gómez V, Andrés Doménech I, Ferreria T, Egger G, Pollitti E, Rivaes R, Rodríguez-González PM (2013) Implementing a dynamic riparian vegetation model in three European river systems. Ecohydrology 6:625-651 doi:10.1002/eco.1331
11. Ginebreda A, Muñoz I, de Alda ML, Brix R, López-Doval J, Barceló D (2010) Environmental risk assessment of pharmaceuticals in rivers: Relationships between hazard indexes and aquatic macroinvertebrate diversity indexes in the Llobregat River (NE Spain). Environ Int 36:153-162 doi:10.1016/j.envint.2009.10.003
12. Gros M, Rodríguez-Mozaz S, Barceló D (2012) Fast and comprehensive multi-residue analysis of a broad range of human and veterinary pharmaceuticals and some of their metabolites in surface and treated waters by ultra-high-performance liquid chromatography coupled to quadrupole-linear ion trap tandem mass spectrometry. J Chromatogr A 1248:104-121 doi:10.1016/j.chroma.2012.05.084
13. Guillén D, Ginebreda A, Farré M, Darbra RM, Petrovic M, Gros M, Barceló D (2012) Prioritization of chemicals in the aquatic environment based on risk assessment: analytical, modeling and regulatory perspective. Sci Total Environ 440:236-252 doi:10.1016/j.scitotenv.2012.06.064
14. Heathwaite AL (2010) Multiple stressors on water availability at global to catchment scales: understanding human impact on nutrient cycles to protect water quality and water availability in the long term. Freshwater Biol 55:241-257 doi:10.1111/j.1365-2427.2009.02368.x
15. Huerta B, Rodríguez-Mozaz S, Barceló D (2012) Pharmaceuticals in biota in the aquatic environment: analytical methods and environmental implications. Anal Bioanal Chem 404:2611-2624 doi:10.1007/s00216-012-6144-y
16. IPCC (2007) Fourth Assessment Report: Climate Change 2007. Cambridge University Press, Cambridge, UK
17. Jurado A, De Gaspari F, Vilarrasa V, Bolster D, Sánchez-Vila X, Fernàndez-Garcia D, Tartakovske DM (2012) Probabilistic analysis of groundwater-related risks at subsurface excavation sites. Engin Geol 125:35-44 doi:10.1016/j.enggeo.2011.10.015
18. López-Doval JC, De Castro-Català N, Andrés-Doménech I, Blasco J, Ginebreda A, Muñoz I (2012) Analysis of monitoring programmes and their suitability for ecotoxicological risk assessment in four Spanish basins. Sci Total Environ 440:194-203 doi:10.1016/j.scitotenv.2012.07.035
19. Maltby L (1999) Studying stress: The importance of organism-level responses. Ecol Appl 9:431-440 doi:10.2307/2641131
20. Martín G, Toja J, Sala SE, de los Reyes Fernández M, Reyes I, Casco M (2010) Application of diatom biotic indices in the Guadalquivir River Basin, a Mediterranean basin. Which one is the most appropriated? Environ Monit Assess 170:519-534 doi:10.1007/s10661-009-1254-5
21. Millenium Ecosystem Assessment (2003) Ecosystems and human well-being: A framework for assessment. Island Press, Washington, DC, USA
22. Navarro-Ortega A, Acuña V, Batalla RJ, Blasco J, Conde C, Elorza FJ, Elosegi A, Francés F, La-Roca F, Muñoz I, Petrovic M, Picó Y, Sabater S, Sánchez-Vila X, Schuhmacher M, Barceló D (2012) Assessing and forecasting the impacts of global change on Mediterranean rivers. The SCARCE Consolider project on Iberian basins. Environ Sci Pollut Res Int 19:918-933 doi:10.1007/s11356-011-0566-5

22b. Navarro-Ortega A, Acuña V, Bellin A, et al. (2015). Managing the effects of multiple stressors on aquatic ecosystems under water scarcity. The GLOBAQUA project. Sci Total Environ 503-504:3-9 doi:10.1016/j.scitotenv.2014.06.081
23. Navarro A, Tauler R, Lacorte S, Barceló D (2010) Occurrence and transport of pesticides and alkylphenols in water samples along the Ebro River Basin. J Hydrol 383:18-29 doi:10.1016/j.jhydrol.2009.06.039
24. Paredes-Arquiola J, Andreu J, Martín-Monerris M, Solera A (2010) Water quantity and quality models applied to the Júcar River basin, Spain. Water Res Manag 24:2759-2779 doi:10.1007/s11269-010-9578-z
25. Petrovic M, Ginebreda A, Acuña V, Batalla RJ, Elosegi A, Guasch H, López de Alda M, Marcé R, Muñoz I, Navarro-Ortega A, Navarro E, Vericat D, Sabater S, Barceló D (2011) Combined scenarios of chemical and ecological quality under water scarcity in Mediterranean rivers. Trend Anal Chem 30:1269-1278 doi:10.1016/j.trac.2011.04.012
26. Poesen JWA, Hooke JM (1997) Erosion, flooding and channel management in Mediterranean environments of southern Europe. Prog Phys Geog 21:157-199 doi:10.1177/030913339702100201
27. Sabater S, Barceló D (2010) Water scarcity in the Mediterranean. In: Sabater S, Barceló D (eds) Perspectives under global change. Springer-Verlag, Berlin doi:10.1007/978-3-642-03971-3
28. Sabater S, Navarro-Ortega A, Barceló D (2011) Oferta y demanda de agua: implicaciones para los sistemas fluviales mediterráneos. Cuadernos de la Fundación General CSIC 4:28-33
29. Sánchez-Canales M, López Benito A, Passuello A, Terrado M, Ziv G, Acuña V, Schuhmacher M, Elorza FJ (2012) Sensitivity analysis of ecosystem service valuation in a Mediterranean watershed. Sci Total Environ 440:140-153 doi:10.1016/j.scitotenv.2012.07.071
30. Tena A, Batalla RJ, Vericat D (2012) Reach-scale suspended sediment balance downstream from dams in a large Mediterranean river. Hydrol Sci J 57:831-849 doi:10.1080/02626667.2012.681784
31. Tena A, Książek L, Vericat D, Batalla RJ (2012) Assessing the geomorphic effects of a flushing flow in a large regulated river. River Res Applic 29: 876-890
32. Vörösmarty CJ, McIntyre PB, Gessner MO, Dudgeon D, Prusevich A, Green P, Glidden S, Bunn SE, Sullivan CA, Liermann CR, Davies PM (2010) Global threats to human water security and river biodiversity. Nature 467:555-561 doi:10.1038/nature09440