Guidance Document (D.3.2): Identified emerging issues from the round table discussion on environmental impacts of water scarcity and droughts. Part of Work Package 3: Environmental Impacts of Drought. XEROCHORE FP7 Project

O. Oliver Olsson, M. Bauer, S. Barchiesi, J. Dalton, J. Froebrich, A. Schrevel, Eric Sauquet, Maria-Helena Ramos

11 Feb. 2010

7^{TH} FRAMEWORK PROGRAMME
THEME 6
Environment (Including Climate Change)

FP7-ENV-2007-1 (ENV.2007.1.3.3.3.)
Grant agreement no.: 211837

Guidance Document (D.3.2)

Identified emerging issues from the round table discussion on environmental impacts of water scarcity and droughts

Part of

Work Package 3: Environmental Impacts of Drought

Oliver Olsson, Melanie Bauer, Water Management Center, Germany
Stefano Barchiesi, James Dalton, International Union for Conservation of Nature, Switzerland
Jochen Froebrich, Aart Schrevel, Wageningen University, The Netherlands
Eric Sauquet, Maria-Helena Ramos, Cemagref, France

Preface

The EU-FP7 XEROCHORE project is a Support Action (SA) that for the first time brings together three interrelated drought aspects at the European scale, namely (1) the natural system (climate and hydrological systems), (2) impacts (socio-economic and environmental), and (3) drought management and policy. It compiles a roadmap that includes the state-of-the-art and identifies research gaps in these three aspects. Moreover, it provides guidance on appropriate responses for stakeholders. XEROCHORE's outcome contributes toward a future European Drought Policy, in accordance with the EU-Water Framework Directive (WFD) and other related EU legislation and actions.

A comprehensive extended network of drought experts (over 80 organizations) gathers inputs to cover the three drought aspects through two focused workshops and a concluding conference. The network includes research institutes, universities, ministries, water management organizations, stakeholders, consultants, international organizations and programs. It includes key members of the European Drought Centre (EDC) and the WFD-CIS Working Group on Water Scarcity and Drought and representatives from overseas and neighboring countries, in particular around the Mediterranean Basin. The large number of organizations covering different aspects and geographic regions guarantees that all of the above-mentioned drought aspects are well covered. The network of drought experts is embedded in the European Drought Centre to enlarge its expert's community and expertise to provide research advice and policy support to the European Commission beyond the lifetime of the XEROCHORE project. XEROCHORE's outcome will contribute towards a future European Drought Policy, in accordance with the EUWater Framework Directive (WFD) and other related EU legislations and actions.

This Extended Guidance Document deals with the second drought aspect, i.e. Environmental Impacts. It is based upon a draft document[1] that provided input to the second XEROCHORE workshop, Venice, Italy, 5-7 October 2009. About 60 workshop participants[2] commented on the draft document. Extensive discussions in several breakout groups and a following plenary meeting eventually led to this Extended Guidance Document on the on the Identified emerging issues from the round table discussion on environmental impacts of water scarcity & droughts. This document subsequently feeds into the final conference on drought management and policy (Brussels, February 2010).

[1] Olsson et al., Background Document - Environmental Impacts of droughts - State of the art review. (XEROCHORE Deliverable D.3.1), September 2009.

[2] Annex 7.5 provides the list of persons who contributed to this Extended Guidance Document on the Identified emerging issues from the round table discussion on environmental impacts of water scarcity & droughts

Content

Executive Summary

Key challenges for drought planning in the context of sustainable land and water management

Appropriate drought impact-reduction measures are required based on sound and agreed data that is regionally, nationally, and basin-wide applicable. Further investigation should be redirected into the current entry points in drought monitoring systems for integrating multidisciplinary information for the development of drought based environmental indicators. Improvement in hydrological monitoring should recognise the changing climate, possible increase in extremes and multidisciplinary indicators required for drought monitoring as well as the capacity development needs to renew hydrological sciences and other primary institutions responsible for monitoring climate and hydrology. The multidisciplinary scientific programmes required to understand feedback mechanisms for adequate drought planning may include new science areas such as ecohydrology.

There is a need to recognise natural or green infrastructure and the services provided by ecosystems to society and the need for freshwater to preserve those ecosystems. Restoration of degraded ecosystems should be included as part of planning for watershed or river basins that extends across human drawn boundaries and borders. In this context the role of environmental flows for river basin allocation to improve the resilience of ecosystems to drought should be further investigated. Rationalising tools for environmental flows can help develop a suite of approaches relevant to river basins in Europe and integrate their use into basin interventions through Strategic Environmental Assessment regulatory instruments. Likewise, knowledge gaps exist around payments for ecosystem services as a mechanism to distinguish the role of ecosystem services in society and to provide revenue for ecosystem restoration and maintenance of ecosystems through drought periods. Further research may also be required on the cost of droughts and the negative impacts on ecosystems in relation to tourism revenue.

In order to increase socio-economic resilience, buffer climate risks and enable adaptive water management at the same time, sustainable basin management should focus on integrating different elements, e.g environmental flows, upper watershed management and water governance capacity.

Research gaps

Especially in the impact assessment of droughts there is a lot unknown. The complexity of the water-land-cycle and under consideration of hydrological processes adds its bit. Further, it is still difficult to quantify the influence of land use on runoff and water quality respectively, especially over the long term. In this context, the use of existing indices for characterising low flow regimes is still hampered by the lacking knowledge on most relevant variables to preserve water quality and aquatic habitat. It would therefore be valuable if indicators were developed to detect drought conditions across the different climatic zones of Europe vulnerability assessment methodologies under different environmental conditions, including projected climate change for Europe.

In a wider scope there is the need to extend the knowledge on combined effects between droughts and water or soil quality. With still lacking understanding on ecosystem sensitivity, required flow conditions and the missing knowledge how future climate change will worsen the water quality deterioration. Here, some authors suggested to put more emphasise on the examination under what conditions the stream temperature along the length of a river is influenced by fine-scale point processes versus upstream landscape-scale environmental conditions.

The impacts of drought on ecosystem processes are a priority in future research. There is a clear need to better understand how drought alters ecological functions and how these effects are influenced by species composition. In terms of available data on responses to drought in flowing waters, more information is available on invertebrates and fish than on micro- and macroalgae, macrophytes and riparian plants. Knowledge gaps also exist on the effects of long-term droughts on fish and at the spatial scale of river basins to subcontinents. As early warning indicators, further and sustained monitoring of headwater streams macroinvertrebates is needed for a classification of droughts in relation to the impact on surface flows, groundwater levels and rainfall deficits. Further research is also expected on the role of refuge use by fishes in response to drought as well as source-sink population dynamics.

In agroecosystems, research priorities should focus on the prospects for crop and soil management and plant breeding and biotechnology that are needed to achieve high stable yield under drought. One of the aims of drought management policies is also to understand the extent to which livestock mortality in arid lands influences cattle demography. Forestry research should focus on the simultaneous effects of drought and other factors, such as forest management, air pollution and global warming. More generally, a need has been recognized in conservation to shift from site prioritization to managing the whole ecosystem at the river basin level.

Background

The aim of the Guidance Document - Environmental impacts of droughts - is to provide a review of existing background and knowledge on environmental impacts related to drought and to identify research gaps and key challenges for a European Drought Policy.

Droughts have a wide range of impacts, many of which are not direct or clearly understood (e.g. UNDP, 2006). They have a direct impact on the environment, economy, and society more generally. Impacts will likely get worse with the predicted climate change (IPCC, 2007a; 2007b) and the increasing population and societies' rising water demands, a situation exacerbated by the need to maintain water availability. A wide range of different types of environmental impacts was identified and summarised in an "Impact Matrix" that distinguish between direct and indirect impacts.

The Water Framework Directive creates a framework for protecting water resources aiming to protect ecosystems, promoting long-term sustainability of water use, improving the aquatic environment, and mitigating the effects of floods and droughts. Although water scarcity management and droughts management are not primary objectives of the WFD, Article 1.e states the need to mitigate the effects of floods and droughts.

However, focusing on impacts and their relevance for supporting the set-up of an European Drought Policy the document has reviewed in more detail the following aspects:

- Impacts of droughts on the physical environment.
- Impacts of droughts on ecosystem.
- Impacts of droughts across different climatic conditions in Europe and Worldwide.
- Strategies for reducing vulnerabilities to drought.

This summary deliver insight into the main impacts and issues discussed and presented in the comprehensive Guidance Document on 'Identified emerging issues from the round table discussion on environmental impacts of water scarcity and droughts'.

Impacts of droughts on the physical environment.

Water scarcity conditions and droughts can occur everywhere in Europe, yet the intensity with which they will occur is different, and that is also true for their effects. The climate of the Mediterranean region, already relatively hot and dry to begin with, is predicted to become noticeably hotter and dryer (e.g. Bates et al., 2008). The northern countries and the mountainous regions of Europe will generally become warmer also, which may lead to less water being kept in snow layers, more run off as a result, and thus increasing occurrences of droughts in the summer. In Central and Eastern Europe, summer precipitation is projected to decrease, causing higher water deficits.

Impacts of droughts on water quantity

The impact of climate change on hydrology has been studied widely, with a clear focus on water quantity. This review complements the Xerochore Guidance Document "Natural System" on the reduced water availability in surface waters for environmental minimum flow. The direct impact of droughts on water quantity is the reduction of water volumes, which reduces available hydraulic connectivity, water levels and flows. This affects and reduces the ability for fish move more freely through their ecosystem, navigable waters for commercial and recreational purposes.

Impacts of droughts on water quality

The state of the art demonstrates that, still, few studies have been reported that assessed the impact of droughts and inherent low-flow conditions on river water quality. Since river water quality may deteriorate to critical values during periods of prolonged low-flow conditions in combination with high water temperatures, insight and understanding of the impact of droughts on water quality is essential, especially for rivers, which are highly sensitive to drought conditions.

The identified studies have indicated that water quality can be directly affected by several climate-related mechanisms over both short and long term time periods. These include effects of air temperature increase, as well as changes in hydrological factors (e.g. limited dilution of point source polluting emissions during low river flows), terrestrial factors (e.g. changes in vegetation and soil structure) and resource-use factors (e.g. increased water use, increased demand for cooling water, etc.).

Soil – water interrelations

The management of land, water and related resources is intrinsically tied among each other. For example land use constitutes one of the factors influencing runoff and water quality at the watershed level or deforestation of one piece of land for agricultural or urban development can affect local water balance and pollutant fate. It is therefore apparent how managing river basins in an integrated fashion is vital to buffer against the effects of drought on land-river aspects such as soil water, content, ephemeral water bodies, sediment transport and habitat suitability of biota.

Soil water deficiency: Soil is vital for land and water management, ranging from agriculture to urban growth areas and the construction industry. Droughts imply a reduction of water, not only in rivers and lakes but also in the soil. This in turn negatively affects soil fertility and therefore biodiversity. Reduced soil structure also reduces water holding capacity and may increase the risk of erosion, especially where higher wind speeds occur during drought. Water is therefore a distinguished stress factor of soils defining of positive or negative soil-water stresses.

Sediment transport in Rivers and Reservoirs: A reduced flow as effect of droughts can cause a decrease in the transport of fine particulate with a risk of accumulation, and interstices of the substrate in pools and in reservoirs. Such deposits may reduce the quality of fish habitat and cause significant changes in the ecosystem.

Impacts of droughts on ecosystems.

Biological conditions - The natural environment

Disturbance regimes such as drought influence the structure and functions of freshwater ecosystems through different abiotic and biotic factors. These factors compose the geomorphic, chemical, and terrestrial features of catchments, let alone human land use. As an ecological disturbance, drought has both direct and indirect effects on streams. Direct effects include loss of water, loss of habitat for aquatic organisms and loss of stream connectivity. Indirect effects include the deterioration of water quality, alteration of food resources, and changes in the strength and structure of inter-specific interactions. Natural terrestrial ecosystems and agrosystems are also affected by drought.

Impacts of droughts on flowing water ecosystems: The effects of drought on naturally flowing streams depend on many factors, including: rainfall patterns, the amount of water entering the stream especially from below-ground sources, groundwater levels, and the nature of the stream bed. Whether the water level drops in the stream channel, wet-season flooding does not occur, or the water course ceases to flow altogether, progressive consequences on ecosystems will be entailed. Changes to standing water conditions can cause severe stress to plants and animals that are more used to living in water that is flowing. This is until the assemblage of invertebrate fauna becomes more similar to that normally found in standing waters where biotic interactions seem to be much more evident than in lotic communities.

Impacts of droughts on standing water ecosystems: Drought can have major ecological effects in standing waters and their inhabitants. Both lenthic flora and fauna is stressed and depleted by stranding, increase in salts and suspended solids concentrations, and toxic algal blooming resulting from the release of nutrients from sediments. When longitudinal fragmentation of stream habitats prevents the normal transport of nutrients, biota and organic matter down river channels, different conditions are often created in each pool. Pools that persist throughout the drought are known as drought refuges or refugia. These are critical habitats to the survival of many species in drought-prone rivers and wetlands.

Impacts of droughts on terrestrial ecosystems: Different mechanisms of drought resistance exist for terrestrial biodiversity. Examples for animals comprise thermo-regulation, moving to more protected areas and summer diapause. Although extreme weather events such as drought appear to drive local population dynamics, knowledge of precise causal factors of species' response to climate change is largely unavailable except for two groups of animals, i.e. the Lepidoptera and birds. Production of antioxidant and compatible compounds, changes in cell membrane composition, rapid defoliation, morphological adaptation e.g. deep-rooting and seed banking have been listed as drought-coping strategies for plants. Carbon balance and insect resistance are also considered as key variables in survival and mortality mechanisms of plant regulation of water use. Another important element of indirect drought impacts on local forest dynamics is the increased frequency of fires.

Ecosystem vulnerability and resilience to drought

Loss of resilience can be described as through the combined and often synergistic effects of the pressures that can make ecosystems more vulnerable to changes whereas those could previously be absorbed. Hence resilience reflects the degree to which a complex adaptive system is capable of self- and re-organising.

Ecosystem thresholds and regime shifts: When analysing the potential for reorganization, the diversity of functional groups, the diversity within species and populations, and the diversity of species within functional groups appear to be critical for resilience and the generation of ecosystem services. Change in drought frequency and magnitude influences the species composition and structure of ecosystems through population declines, loss of habitat, changes in the community, negative effects from changes in water quality, movement within catchments, and crowding in reduced microhabitats. Ecosystems will therefore be as resilient as the extent of disturbance that they can experience before shifting into a different state.

Species adaptations and refuge habitats: Drought produces a decrease in habitat area/volume and an increase in extremes of the physical and chemical water quality parameters of low-flow or dry season refugia. These conditions are linked with biotic interactions such as competition and predation that structure animal communities by increasing mortality rates, decreasing birth rates and/or increasing migration rates. From a species perspective, ecosystem responses such as shifts in vegetation types imply changes in habitat quality and distribution. When climate conditions change beyond species' breadth of tolerance, species may be forced to respond by shifting the timing of life-cycle events, shifting their geographical boundaries, changing morphology, behaviour or their genetic make up. When neither adaptation nor shifting range is possible, extinction is a likely scenario. When some of the normally used habitat areas are removed by drought, biota become restricted to isolated 'refuge habitats'.

Ecological responses and recovery from drought: Drought as perturbation consists of the disturbance, i.e. the impacts on ecosystems of the decline in water availability, and the biotic responses to the disturbance. The response may be viewed as covering two forms of response. Resistance is the capacity of the biota to withstand the drought. Resilience is the capacity of biota to recover from drought. Resilience rather than resistance is key to the persistence of mobile animals. Temporary wetland organisms can either escape in space through active migration and dispersal or escape in time through drought-resistant life history stages such as dormant plant seeds and diapausing invertebrate resting eggs. Recovery of biota from seasonal droughts follows predictable sequences, whilst recovery from supra-seasonal droughts may be marked by altered species assemblages.

Impacts of droughts across different climatic conditions in Europe.

Climate and drought are closely connected. Indeed, the way drought develop in time and space depends is mainly governed by the meteorological processes. Drought results from lack of precipitation high temperature anomalies in the warm season and low temperature anomalies in the cold season during an extended period.

Each drought has its own specificities and its impact on the environment depends on the severity, the duration and the occurrence. In addition, some regions are more vulnerable than others, both to expected physical changes and to the consequences they will have for ways of life. In particular, mountainous regions are recognized as particularly sensitive physical environments with populations whose histories and current social positions often strain local capacity to accommodate intense and rapid changes to their resource base.

Recent studies show the impacts of droughts on ecosystem under different climates. There are further some indicative examples for impacts of droughts in different climatic regions. For example, runoff in the Canadian prairies is over 80% derived from snowmelt. Wetlands fill the depression in wet years and are underlain by a heavy glacial till that impedes groundwater exchange. Results showed that in times of a severe drought much lower precipitation and snow accumulation, shorter snow-covered duration, enhanced winter evaporation, and much lower discharge to the wetland from basin snowmelt runoff is developed. Another example demonstrates the impacts of shorter-term climate perturbations can disrupt important coastal ecosystem processes. Over repeated drought cycles, such perturbations potentially affected the structure and function of mangrove forests and upstream ecosystems. Reduction in freshwater flows, associated drawdown in the water table and increased salinity near the surface are thought to reduce productivity in mangroves accustomed to flushing and nutrient/sediment inputs from freshwater flows.

Strategies for reducing vulnerabilities to drought.

The impacts of drought on ecosystems are inherently linked to ecological and related socio-economic vulnerabilities, such as those entailing water use restrictions, supply cuts and water re-allocations. Environment allocations of water are intended to maintain biodiversity, but also the provisioning services upon which society functions at a productive and livelihood level. The flow regime in rivers and streams is often the most critical element of understanding ecosystems services and a link to resilience that gives the environment a critical role in climate change adaptation. In order to accrue these benefits 'from a river', society must provide benefits 'to the river' through maintaining healthy and sustainable river basins which incorporate management strategies for drought periods. In this respect, a number of key policy challenges have been identified for drought planning in the context of sustainable land and water management that relate with natural catchments as additional sources of water supply.

Drought management in the context of sustainable land and water management

Eco-hydrology and ecological engineering: One of the fundamental concepts involved in ecohydrology is that the timing and availability of freshwater is intimately linked to ecosystem processes, and the goods and services provided by freshwater to societies. Ecohydrology is a science gaining recognition in the multidisciplinary areas between natural processes and engineering solutions to reduce environmental impact and to better understand ecological responses. From an aquatic viewpoint, ecohydrology considers the relationships between hydrology and the ecological processes and their biota. Terrestrial ecohydrology focuses more on ecological processes involved within the hydrological cycle with an emphasis on evapo-transpiration, canopy interception, and thermodynamic balance at the land surface.

Ecosystem-based water management: The combination of different categories of impacts such as climate-led modifications of the hydrological cycle, hydropower operations, and water withdrawals for irrigation erodes the self-repairing capacity of ecosystems until they cease to cope with ordinary change such as climate variability. The Ecosystem Approach is a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way. The management of ecosystems under drought conditions is a three-step process whereby including the identification of key indicators of ecosystem health, the application of methods for defining reference conditions and restoration strategies, and the development of a decision support system to respond to the interactions between climate and other changes.

Drought indicators and restoration strategies: It is not known if any of the drought monitoring indices currently under development or early warning systems include elements on environmental impacts or ecosystem indicators at regional down to local scales. At a catchment scale, spatially variable soil hydrologic processes and land-use cause spatial variability of evapotranspiration and subsequently, of soil moisture content and of groundwater recharge. As competition between sectors over water will most likely increase, indicators will also need to take into account the water needs of all sectors, including the environment as a major water user and provider of ecosystem services. Among the many valuable services that healthy ecosystems provide besides preserving biodiversity is storage of water. Particular attention should be paid to the role of green infrastructure in increasing resilience to drought.

Environmental flows: The recognition of the escalating hydrological alteration of rivers on a global scale and resultant environmental degradation has led to the establishment of the science of environmental flow assessment. Environmental flows describes the quantity, quality and timing of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems. Environmental flow assessments can serve as a decision-support tool that mainstreams both ecosystems needs and climate change scenarios into water resources management. Holistic methodologies include considerations of ecosystem-dependent livelihoods and a benchmarking process suitable for evaluating alternative water resource developments at basin scale. Existing and planned water projects represent opportunities to conduct ecosystem-scale experiments through controlled river flow manipulations.

Building drought into river operational plans: River operational plans exist which take into account the balance of water allocation for extraction such as for urban use or irrigation and water for the environment as well as the rules for managing this balance. However, water managers have the additional challenge to decide whether, when and where in the catchment to provide environmental flows to relieve stress in the river ecology. Altered flow regimes have ecological consequences for aquatic biodiversity when they modify the physical habitat, life history patterns, and natural spatial connectivity or encourage invasion by alien species. In many basins, flows regimes are still classified by only following simple hydrological criteria without considering the requirements of ecosystems in relation to temporal distribution and water quality. Any reduction in minimum flows required to preserved waterbody ecological status should be previously analysed to determine the negative effects of the changes on the ecological status including aquatic fauna and flora.

Integrated Water Resources Management (IWRM): Catchments, basins and groundwater recharge areas are the natural units for IWRM. This is to understand and balance competing water uses and to mobilize meaningful stakeholder and public participation across administrative and human defined boundaries. The EU Water Framework Directive is concerned with protection and restoration of rivers, but hydrological modification is not used to assess the ecological status of the river. Therefore, alterations in flow regime e.g. extraction will not affect the status of the river unless the actual biology is affected. Restoring more natural flow patterns through applying environmental flows may improve the ecological status of some rivers. Recovery needs should also be considered in basin where allocations already exceed water availability and leave no water for environmental flows, especially during drought periods.

Introduction

Climate change projections for Europe indicate that drought is likely to become more frequent and more severe due to the increased likelihood of warmer Northern winters and hotter Mediterranean summer. This will lead to significant socio-economic and environmental impacts (Bates et al., 2008). The record-breaking drought event in 2003 was a strong reminder of Europe's vulnerability to drought with serious impacts on society, environment and various economic sectors. The heat wave that accompanied it contributed to the deaths of more than 30,000 people (Kosatsky, 2005; Black et al., 2004).

Droughts have a wide range of impacts, many of which are not direct or clearly understood (e.g. UNDP, 2006). They affect the environment (e.g. water quantity, water quality, aquatic ecosystems, wetlands, forest fires), the economy (e.g. rain-fed and irrigated agriculture, forestry, energy sector (hydropower, cooling water), waterborne transport, water supply, tourism) and society more generally (e.g. health, poverty). Impacts will likely get worse with the predicted climate change (IPCC, 2007a; 2007b) and the increasing population and societies' rising water demands, a situation exacerbated by the need to maintain water availability.

The environmental impact of droughts ranges from changing abiotic conditions (water quantity and quality) until direct impacts on plants (desertification) and fauna. Modern concepts such as the disturbance hypothesis and panarchy indicated the relevance of spatio-temporal variability and transformative change. The interaction between aquatic and terrestrial components is also a key-aspect for ecosystems to be resilient against occurring water deficits. In humid climate areas, future increases in drought duration, frequency and (build-up) deficit volumes may result in dramatic ecological changes, especially where ecosystems and their plant and animal populations are less adapted to severe disturbances. Under arid and semi-arid conditions, future proliferation of exceptional droughts and increase in drought frequency may result in the disappearance of refugia and key-stone species. This could lead to rapid and irreversible transformations of entire ecosystems.

The WFD creates a framework for protecting water resources with the goals of protecting ecosystems, promoting long-term sustainability of water use, improving the aquatic environment, and mitigating the effects of floods and droughts.

Article 1.e of the WFD states the need to mitigate the effects of floods and droughts. However, water scarcity management and droughts management are not primary objectives of the WFD, which is the directive to achieve good ecological and chemical status of surface water bodies, and chemical and quantitative status of groundwater. Good ecological and chemical status is to be achieved even under conditions of water scarcity and the occurrence of droughts, which makes water scarcity and drought more an extraneous factor. Yet, droughts interfere with a member state's ability to improve or prevent deterioration in the status of bodies of water. The WFD additionally considers that prolonged droughts are "… grounds for exemptions from the requirement to prevent further requirement to prevent further deterioration and to achieve good status" (Preamble 32); and the measures that directly relate to drought mitigation are left as optional supplementary measures (WFD Annex VI, Part 5)[3].

Therefore the main objective of this Guidance Document is to discuss a group of selected environmental impacts in more detail supporting the Xerochore roadmap compilation that provides a short to long term vision on research needs and steps forward towards supporting the implementation of drought management plans within the WFD development as a result of a European drought policy.

For setting up a conceptual framework for droughts and to provide links and relationships to already and well known structures, the phenomenon of 'drought' is put in the context of the DPSIR Framework (Driving Forces-Pressures-States-Impacts-Responses). Those framework represents the

[3]Mediterranean water scarcity and drought working group (Med WS and D WG), 2007, Mediterranean water scarcity and drought report, Technical report on water scarcity and drought management in the Mediterranean and the Water Framework Directive, Technical Report 009-2007

enlargement of the PSR model (Rump, 1996), and the recommendation from the OECD (1993, 1994 and 1996) by the European Environmental Agency (1999).

The framework is seen as giving a structure for linking related environmental issues within which to present the indicators needed to enable feedback to policy makers on environmental quality and the resulting impact of the political choices made, or to be made in the future.

Therefore, in the context of droughts consideration of the decision-making, or policy cycle has to be woven into this framework.

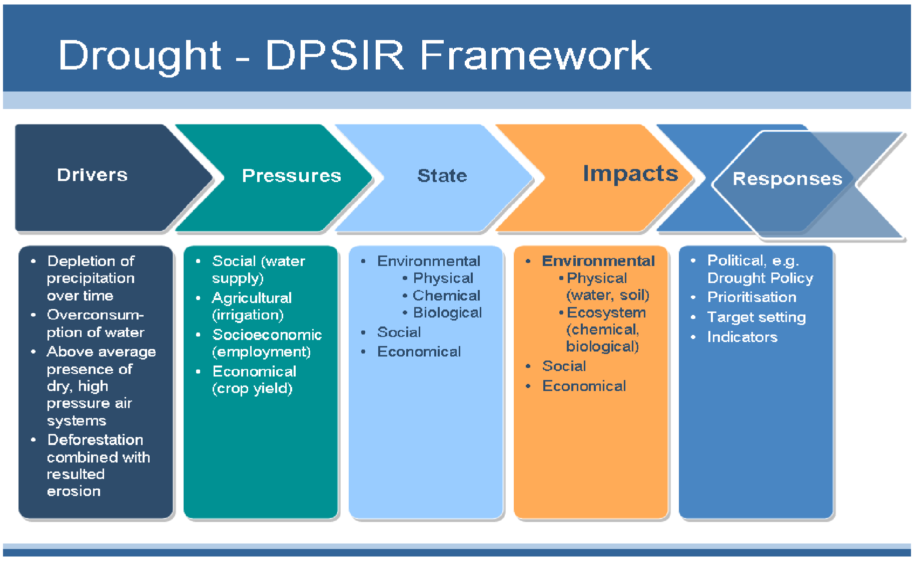

Figure: Scheme of the Driving-Forces-Pressures-States-Impacts-Responses (DPSIR) model for drought.

The 'Driving-Forces-Pressures-States-Impacts-Responses' model is herein transferred to the characterisations of droughts. The framework describes a chain of causal links of factors providing the interactions between society and the environment in case of a drought or dry conditions.

With the help of the causal framework and the knowledge of specific chain of interactions a drought assessment should be built up, focussing on limiting elements and by this improving the dialogue between researchers, water managers and policy makers, and finally leading to recommendations of the issues to be covered during the set-up of a drought policy.

General predefinitions for the document

This Guidance Document provides an overview on the identified environmental impacts of droughts and summarises the outcomes of the state of the art review within an "Impact Matrix". The impact matrix was developed based on the understanding that drought is a primary consequence of low or no precipitation (Wilhite and Buchanan-Smith, 2005). Although reduced precipitation is the primary cause of drought, it often combines with increased air temperatures, and this may lead to increased wind speeds and frequency. The impact matrix (Annex 8.1) identifies the direct impacts on the environment based on three parameters or mechanisms of drought: (i) low precipitation; (ii) increased air temperature; and (iii) increasing wind speed and/or frequency.

The impact matrix also attempts to identify the indirect impacts of drought on the environment in two stages. Indirect Impacts (1) may not always be a direct result of drought, although drought can contribute to these impacts where there are other contributing factors, such as poor land management practices, pollution of watercourses, over-extraction of water, etc already occurring. Indirect Impacts (2) are a result of direct or indirect initial impacts of drought. Furthermore, indirect impacts could start a chain reaction event not identified as a consequence of drought (e.g.: possible rodent infestations;

Greaves, 1989). Attribution of drought impacts is therefore complex given the slow development of drought and the different impacts on the environment depending on the hydrogeology, hydrology, climate (altitude), length and intensity of the drought, ecosystem and habitat diversity, and the reliance on freshwater resources and modification of the natural basin hydrology by human development.

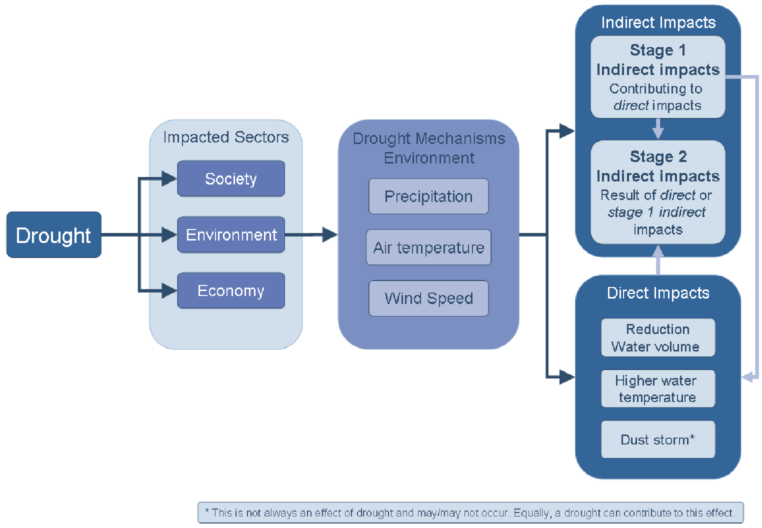

Figure: Applied concept for the classification of direct and indirect impacts of droughts on environment (Annex 7.1).

Because there exist a wide range of different types of impacts it is necessary and important to distinguish between direct/ indirect or primary/secondary impacts and their relevance for drought management plans within the EU-Water Framework Directive (WFD) development.

According to these objectives this document focus on existing knowledge on environmental impacts of droughts, which can be categorised as (i) damages to physical environments (quantitative and qualitatively effects on water bodies), (ii) damages to ecosystems (plant and animal species), (iii) impacts on the interaction between aquatic and terrestrial components, and (iv) consequences for different climatic regions in Europe.

1. Impacts of droughts on the physical environment (quantity and quality)

This section provides a summarised review of the impact of droughts on water quality and identifies research gaps for securing water quality under drought. The state of the art demonstrates that, still, few studies have been reported that assessed the impact of droughts and inherent low-flow conditions on river water quality (Caruso, 2002). Since river water quality may deteriorate to critical values during periods of prolonged low-flow conditions in combination with high water temperatures (e.g. Somville and De Pauw, 1982), insight and understanding of the impact of droughts on water quality is essential, especially for rivers, which are highly sensitive to drought conditions.

Common patterns of increases in concentrations of chemicals released by point sources (e.g. fluoride, chloride, ammonium) were generally consistent with findings of other studies for river systems in New Zealand and North America (Caruso, 2002, Murdoch et al., 2000 and Schindler, 1997), reflecting a decrease in dilution during droughts. Additionally, decreases in concentrations of substances primarily released by diffuse sources (e.g. nitrate) and substances adsorbed to suspended solids (e.g. heavy metals) were also mentioned by Mulholland et al. (1997) for freshwater systems in the South-Eastern United States. They also explained their findings by less supply by soil leaching and overland flow, and lower suspended solid concentrations under drought conditions.

Recently, the potential effects of climate change on surface water quality have been increasingly acknowledged (e.g. Murdoch et al., 2000). The impact of climate change on hydrology has been studied widely, with a clear focus on water quantity, e.g. Pfister et al. (2004), Middelkoop et al., (2001) and Gellens and Roulin, (1998). Global climate change is set to increase frequency and severity of low flow in some regions and regions most likely affected are those that already have low rainfall and intermittent periods of drought (Easterling et al., 2000; Lioubimtseva, 2004; Sheffield and Wood, 2008).

For a majority of complex systems, determining effects of climate change is difficult (Hulme et al., 1999). However, taking advantage of current weather anomalies to gain insight into future impacts is critical (Ciais et al., 2005). The review of the art has identified several proposed methods assessing potential changes in water quality due to climate change. Examples include empirical relations between water quality and climatic trends (Fukushima et al., 2000), (Schindler et al., 1996) and (Williams et al., 1996), and black-box or deterministic modelling approaches to assess the potential effects of climate change on surface water quality at continental or regional scale (Krysanova et al., 2004, Mimikou et al., 2000, Clair and Ehrman, 1996 and Wolford and Bales, 1996).

These studies have indicated that water quality can be directly affected by several climate-related mechanisms over both short and long term time periods. These include effects of air temperature increase, as well as changes in hydrological factors (e.g. limited dilution of point source polluting emissions during low river flows), terrestrial factors (e.g. changes in vegetation and soil structure) and resource-use factors (e.g. increased water use, increased demand for cooling water, etc.) (Murdoch et al., 2000).

1.1. Water quantity

This section complements the Xerochore Guidance Document “Natural System” and the review of identified impacts of drought (Impact Matrix, Annex I) on the reduced water availability in surface waters for environmental minimum flow.

1.1.1. Surface Water (rivers, lakes and reservoirs)

The direct impact of droughts on water quantity is the reduction of water volumes, which reduces available hydraulic connectivity, water levels and flows. This affects and reduces the ability for fish move more freely through their ecosystem, navigable waters for commercial and recreational purposes.

The aspect of environmental flow becomes more and more important in Europe especially on a national level because of the requirement to implement the Water Framework Directive (WFD) by transposition in national law. On the other hand the need of maintaining a minimum flow for serving ecological needs brought EFR into the light of recognition in the past years, whereby in other countries outside Europe, especially in the dry regions of the USA and Australia this topic is of large interest since a long time.

Box 1 - Indicative examples of the impacts of drought on river flow

The 2003 heatwave in Europe, attributable to global warming (Schär et al., 2004), was accompanied by annual precipitation deficits up to 300 mm. This drought contributed to the estimated 30% reduction in gross primary production of terrestrial ecosystems over Europe (Ciais et al., 2005). Many major rivers (e.g., the Po, Rhine, Loire and Danube) were at record low levels, resulting in disruption of inland navigation, irrigation and power plant cooling (Beniston and Diaz, 2004; Zebisch et al., 2005). The extreme glacier melt in the Alps prevented even lower flows of the Danube and Rhine Rivers (Fink et al., 2004), and drought caused navigation problems in the Po River in Italy when water levels were several meters lower than normal and sediment laden (Barber et al, 2006).

Standing water bodies may shrink in volume and in surface area and may even dry out; a function of size and depth. Changes in lake levels reflect changes in the seasonal distribution of river inflows, precipitation and evaporation, in some cases integrated over many years. Reduction in evaporative and seepage losses from reservoirs is particularly important and valuable during a drought (Kelley, 1986). The major losses of water from a reservoir during a drought are evaporation to the atmosphere and seepage to groundwater. Water bodies such as ponds and shallow wetlands may rapidly dry out completely.

A method for minimizing those losses are given by so called “drought storage allocation rules” aiming to minimize evaporative and seepage water losses from a system of reservoirs. Those are likely to be valuable during a prolonged drought, when the value of lost water is likely to be highest. Typically, concentrating water storage in one or a few reservoirs minimizes overall water losses compared to “balancing” storage among reservoirs. Paradoxically, concentrating storage during a drought tends to minimize the overall reservoir surface area, which tends to minimize reservoir area available for recreation, and increase recreation losses, even as it minimizes water losses. Such rules are likely to require advance agreements to accommodate multiple water uses and right holders (Lund, 2006).

Similar difficulties can arise for hydropower, environmental, or other operating purposes. In addition, changes to normal storage operations to reduce evaporative or seepage losses are likely to require prearranged agreements with water-right holders, regulators, and other interested parties in a system. This points to the importance of having contingency plans and agreements in place before the occurrence of a drought (Lund, 2006).

1.1.2. Groundwater

In general the primary cause for a hydrological drought is the lack of precipitation over a large area and for an extensive period of time, often followed by a reduction of groundwater recharge.

Droughts may lead to the so-called water scarcity, defined as a shortage in the availability of freshwater relative to demand.

Generally, in lowland watersheds subsurface flow components become very important, and the runoff process is often controlled by the interplay between surface and subsurface water and ground water flow. The direction and the intensity of exchange between stream and groundwater flow is regulated by hydraulic gradient, permeability and porosity of the upper soil and groundwater layers. Normally, base flow or groundwater runoff indicates the water volume which has passed into the ground and discharged into a stream or lake from the saturated zone, assuming that groundwater level is higher then the surface water table. But temporarily dry climate and/or anthropogenic influences can lead to decreasing groundwater levels and hence to effluent conditions and water leakage into the subsurface. Thus, base flow is partly decoupled from the runoff composition, which must be taken into account.

To estimate base flow, one has to consider, that the surface and the subsurface watersheds do not always coincide, and the calculation of water balances based on surface watershed areas only can lead to large errors. Groundwater watersheds are not as easily defined as surface watersheds because of subsurface flow in aquifer systems possibly superimposing on each other. Groundwater divides may move in response to dynamic recharge and discharge conditions.

Decreasing groundwater recharge and elevated water temperature could lead to disruption of flow permanency and to an increase of temporary stream stretches.

1.1.3. Mountainous areas

Mountainous and upland regions have an important hydrological function in terms of water provision. Many important river catchments have their sources in these areas which are often associated with relatively high rates of precipitation. In some regions water from melting snow and ice can help to regulate water flows during the warmer summer months. In mountain regions, increasing temperatures under climate change are likely to alter the balance between water sources (rain, ice-melt, snowmelt, groundwater) - particularly modifying the amount and duration of snow cover and the magnitude and timing of peak ice-melt (Melack et al., 1997; Brown et al., 2005). These factors have therefore an impact on the available runoff volume and on the temporal availability of melt-water. Among other consequences are a shortened and earlier snow and ice melt, which increases flooding and causes water availability problems at other times of the year. At higher altitudes, the opposite can be a problem, where increased winter precipitation delays the snow melt, causing difficulties for spring migrations.

The enhanced melting, as well as the increased length of the melt season of glaciers, leads at first to increased river runoff and discharge peaks, while in the longer time-frame (decadal to century scale), glacier runoff is expected to decrease (Jansson et al., 2003).

Box 2 - Indicative examples of the impacts of drought on alpine rivers

According to Rogora et al. (2008) alpine rivers could experience major changes in their hydrological regime in a changing climate. Scenarios provided by regional climate models and measured data available for study sites in Lombardy and Piedmont in Northern Italy show a tendency towards reduced precipitation, mainly in winter and summer, and increasing occurrence of droughts (Rogora et al., 2004; Ambrosetti et al., 2006). Based on their findings, surface waters in the alpine area could be extremely sensitive to a climate warming scenarios, with higher temperatures increasing the frequency of drought which could exacerbate the effects of habitual N deposition on surface water ecosystems.

1.2. Water quality

Although much attention is focused on the physical availability of water supplies during a drought, the potentially deleterious effects of drought conditions on water quality also are a concern. Potential changes in water environment in highly populated regions are of major concern, especially in the areas which supply water resources, where even minor climatic changes might increase the possibility of drought and/or deteriorate the quality of water resources (Smith and Tirpak, 1989).

1.2.1. River water quality

Decreased streamflows could lead to decreased dilution of chemical constituents entering the stream through surface runoff, point source discharges, or ground water. The risk of reaching high levels of pollutant in water bodies is then exacerbated. In addition, smaller volumes of water in a stream (resulting from hydrological droughts) could lead to higher instream water temperatures depending on the season (winter drought do not lead to higher temperatures) and the occurrence of heat waves. The combination of higher water temperatures and increased nutrient concentrations also could lead to increased primary productivity, which in turn could lead to increased dissolved oxygen and pH levels during the day and decreased dissolved oxygen and pH levels at night (Whitehead et al., 2009).

The water quality parameters considered are relevant both with respect to the drinking water function and the ecological status. They can be grouped into 4 categories: (a) general water quality variables (e.g. water temperature, dissolved oxygen, chlorophyll-a), (b) major ions (e.g. chloride, sodium, sulfate, fluoride), (c) nutrients, and (d) heavy metals or other toxics.

Box 3- Indicative examples of the impacts of drought on river water quality

River Rhine: Zwolsman and van Bokhoven (2007) found out for River Rhine that water quality is negatively influenced by (summer) droughts, with respect to water temperature, eutrophication, major ions and heavy metals. Effects on nutrient concentrations were small for ammonium and could not be demonstrated for nitrate, nitrite and phosphate. The decline in water quality during summer droughts is both related to the high water temperatures and to low river discharges (limited dilution of the chemical load from point sources). Moreover, the impact of the 1976 drought on water quality was far more important than that of the 2003 drought, indicating that the impact of droughts on water quality will be greater when the water quality is already poor.

Meuse river: Another case study example shown by van Vliet and Zwolsman (2008) confirms those results by indicating a general deterioration of the water quality of the Meuse river during droughts, with respect to water temperature, eutrophication, major elements, and some heavy metals and metalloids. This decline in water quality is primarily caused by favourable conditions for the development of algae blooms (high water temperatures, long residence times, high nutrient concentrations) and a reduction of the dilution capacity of point source effluents.

South Platte River Basin: The results from a study carried out by Sprague (2005) indicate that drought conditions did also affect water quality in parts of the South Platte River Basin. All sites monitored during the drought had at least one constituent that was elevated or depressed relative to seasonal historical data; however, the number of elevated or depressed values in the drought data at many sites was not as high as might be expected from such low streamflows. In addition, the pattern of the response during the drought differed across sites in different land uses; forested sites were somewhat more sensitive to drought conditions than urban and agricultural sites.

1.2.2. Estuaries

The effect drought has on estuarine waters that flow from different land-use is largely unknown (Burkholder et al., 2006; Mackay and Cyrus, 2001). As freshwater flowing to estuaries originates from runoff, rainfall (Correll et al., 1999), and some permanent groundwater base flow (Valiela et al., 2000), the water quality and ecology of estuaries is likely to be impaired. Yet understanding how environmental properties and nutrients behave in estuaries under drought conditions is imperative to establishing baselines of data upon which anthropogenic impacts can be assessed (Dayton et al., 1998; Edgar et al., 2004; Pauly, 1995). With a reduction in freshwater inputs to estuaries, the normal salinity gradient can be truncated, elevated salinity can extend up the estuaries and poor water quality may develop due to a drop in freshwater inputs, tidal flushing and exchange with the sea (Attrill et al., 1996; Livingston et al., 1997; Attrill and Power, 2000a; Grange et al., 2000; Peirson et al., 2001). Small estuaries may be disconnected from the sea (Gasith and Resh, 1999, Mackay and Cyrus 2001).

Box 4 - Indicative examples of the impacts of drought on estuarine waters

A recent study carried out by Elsdon et al. (2009) investigated if trends in environmental variables and nutrients exist in estuaries subjected to a six year intensive drought. The authors found out that during drought periods, when freshwater flow into estuaries was low, there were no differences between urban and rural estuaries. Instead, changes in environmental parameters and nutrients within estuaries and over time were stronger than any differences among land-use.

The lack of data on water quality in small coastal estuaries during extensive drought periods inhibits the formation of general patterns and determining future impacts associated with climate change. So it was necessary to hypothesize that estuaries in different land-use will have different environmental properties and nutrients, and that trends exist both spatially along estuaries and temporally within estuaries.

Several methods have been proposed to predict potential changes under altered climate, however no sufficient information on has as yet been given to confront the potential crisis. One approach is to plot the changes in water environment against the climatic trend (Schindler et al., 1996), but this methodology can only be applied to a very few areas, where the changes appear self-evident. The second is to construct forecasting models, either causal type (Takara and Kojiri, 1993; Wolford and Bales, 1996) or blackbox type (Clair and Ehrman, 1996; Poff et al., 1996). Recent drought episodes in Morocco (1980-81, 85-86, 91-92, 94-95, 00-01, and 02-03) caused net declines in dam water reserves, groundwater and limitation to drinking water and irrigation supply. A reduction in water quality due to reduced volumes of water caused fish deaths and disruptions to the service of drinking water treatment plants, increasing waterborne diseases (MEDA Water, 2007).

1.2.3. Lake and reservoir water quality

Rising temperatures are likely to lower water quality in lakes through increased thermal stability and altered mixing patterns, resulting in reduced oxygen concentrations and an increased release of phosphorus from the sediments. However, rising temperatures can also improve water quality during winter/spring due to earlier ice break-up and consequent higher oxygen levels.

Box 5 - Indicative examples of the impacts of drought on lake and reservoir water quality

Fukushima et al. (2000) investigate the effects of global warming on the water environment through statistical relationships between meteorological conditions and lake water quality. Using monitoring data obtained from a shallow eutrophic lake, Lake Kasumigaura, Japan, the deterioration of lake water quality, such as increases in COD (Chemical Oxygen Demand) and decreases in transparency, was quantitatively assessed as corresponding to an increase in air temperature. In addition, the authors showed that higher precipitation led to high nitrogen concentrations on a monthly basis, as well as on a yearly basis, probably induced by both the runoff of soilwater having high concentrations and the lowering of residence times of lake water.

The relationship between meteorological conditions and water quality, in particular the air temperature and water temperature, was found to be linear. The deterioration of lake water quality, such as COD increase and transparency decrease, was predicted quantitatively with a tendency similar to that forecasted for a small and shallow impoundment.

1.2.4. Water temperature and dissolved oxygen

Warming of surface waters, and decreases in dissolved oxygen concentrations during droughts were demonstrated in several studies, like Caruso (2002), Murdoch et al. (2000) and Mulholland et al. (1997). Decreases in dissolved oxygen can be explained by a lower oxygen saturation concentration under higher water temperatures, higher rates of organic matter decomposition, and lower re-aeration rates under low-flow conditions (Mimikou et al., 2000). Ducharne (2008) noted that in the River Seine, discharge reduction increased phytoplankton growth and oxygen deficits. Water warming decreased dissolved oxygen, increased phytoplankton biomass during the growth period, and reduced it afterwards, based on a modelling framework used to analyse the relative influence of water warming and discharge reduction induced by climate change on biogeochemical water quality in Paris and downstream.

Also due to warming, many lakes have exhibited prolonged stratification with decreases in surface layer nutrient concentration, and prolonged depletion of oxygen in deeper layers. Increased water temperature and longer ice-free seasons influence the thermal stratification and internal hydrodynamics of lakes. In warmer years, surface water temperatures are higher, evaporative water loss increases, summer stratification occurs earlier in the season, and thermoclines become shallower. Increases in summer water temperature can increase anoxia in stratified lakes, increase the rate of phosphorus releases from lake-bottom sediments, and cause algal blooms (Whitehead, et al. 2009). Together with changes in actual water flows which affects riparian vegetation and water biota the combined factors can impact on food-webs (Covich, et al., 1999).

In Mediterranean lakes and water bodies the increase in water temperatures and nutrients can cause species migration to cooler northern waters or mountainous regions, possibly leading to eradication of whole populations who are unable to adapt (Isendahl and Schmidt, 2006). In summer 1999, France reported a massive mortality rate of gorgonians (*Eunicella sungularis*) and sponges (WWF France, 2004). The drought of 2005 caused large fish mortalities in Spain and Portugal due to increased water temperatures and low levels of dissolved oxygen. 6,000 dead fish and invertebrates were counted in the San Roque Guardiaro in the Guadalquivir River Basin, and in the rivers Corbones and Guadelete (WWF 2005). In Portugal 12 tons of dead fish were removed from the Monte da Rocha reservoir (Ourique) and 9.4 tons from the Bravura reservoir (Algarve) (Journal Correio da Manha, 2005).

High-altitude alpine lakes are endangered ecosystems that are particularly sensitive to climate change. Expected changes with a likely impact on ecosystems include ph shifts, increased penetration of ultraviolet radiation due to decreased dissolved organic carbon and habitat reduction for cold stenothermic organisms due to warming (Whitehead et al., 2009).

Box 6 - Indicative example of the impacts of drought on water temperature and therefore on the supply of cooling water

Power station cooling water discharge temperatures may exceed permitted temperatures into watercourses with less water and higher temperatures than normal.

In France, researches carried out by the French energy producer (Electricité de France) have focused on the impact of warm water release downstream nuclear plants. These studies include trend detection in the Alpine area (Poirel et al., 2008) and water temperature modelling at local site using a deterministic model based on heat budget equation (Gosse et al., 2008). Water temperature control is of great importance since restrictions on water release and abstraction are applied when this parameter exceeds a fixed legal level.

The implications of drought on the reliability of electricity generation are not well documented or researched. The National Drought Policy Commission (2001) highlight the impacts of drought on hydropower generation, including the impact on dam levels and on recreational waters in the Great Lakes area of the United States. Furthermore, where power is generated from dams and sold/transferred across international borders, the impact of drought on power generation needs to be considered in the operational activities of power providers. In Morocco droughts between 1980 and 2001 interrupted hydroelectric production due to water stock decline and fall height of dams. MEDA Water (2007) claim that the impact on electricity and agricultural production contributed to an overall reduction in GDP. Anderson (2008) claims that changes in air temperature will affect seasonal electricity demand patterns and this may affect dam storage and release patterns, further altering once natural river flow regimes.

1.2.5. Impact on water quality deterioration (Nutrients/ DOC/ Turbidity)

As already said, only few studies have focused specifically on the links between drought and water quality. Most of the recent studies are motivated by the problems of climate change (Senhorst and Zwolsman, 2005). Van Vliet and Zwolsman (2008) examine water quality data collected during the droughts of 1976 and 2003 in Europe. Concentrations observed during these two main events are compared to the ones recorded during reference years (1976, 1977, 2002, 2003). They find that values during 1976 and 2003 are significantly different from the values observed during the four adjacent years. Empirical relations are derived to assess the effect of water temperature and discharge on water quality parameters. They demonstrate that water quality is significantly deteriorated during severe droughts.

In water bodies deep enough to persist in drought, the water levels steadily drop exposing the littoral zone, its sediments and its macrophytes to drying. Such water-level recessions may cause the oxidation and mineralisation of organic phosphates (De Groot and Van Wijck, 1993), resulting in the release of phosphate when the drought breaks. Nitrogen as nitrate may accumulate in the sediments, and both denitrification and ammonification (from organic N) may occur in the deeper anoxic sediments (de Groot and Van Wijck 1993, McGowan et al., 2005). In an experimental study of a winter drought in Canada, McGowan et al. (2005) found that with the drought breaking, there were increased ammonium-N concentrations in the lake’s water, but no significant changes in other chemical attributes (PO4 –P, NO3-N, total dissolved nitrogen, total dissolved carbon).

DOC

Climate change has also been proposed to explain recent, widespread increases in concentrations of Dissolved Organic Carbon (DOC) in surface waters. Montheith et al. (2007) found, however, that changes in the chemistry of atmospheric deposition provided the only regionally consistent explanation for the upward trends in surface water DOC concentrations in time series data from 522 remote lakes and streams in North America and northern Europe. Their findings suggest that threats of widespread destabilization of terrestrial carbon reserves by gradual rises in air temperature or CO2 concentration may have been overstated (Monteith et al., 2007).

In acid lakes in Florida during drought, James (1991) observed that anoxic hypolimnia developed in lakes with high dissolved organic carbon (DOC) levels and bacterial levels. With the breaking of the drought DOC levels rose whereas bacterial levels dropped, possibly because of inhibitory effects of DOC, including polyphenols, at the high concentrations.

Turbidity

In the water column of lakes, turbidity may increase due to mobilisation of previously inundated sediments. In a south Florida estuary, Livingston et al. (1997) found that with drought, turbidity of the estuary greatly declined allowing greater light penetration into the water increasing primary productivity.

Box 7 - Indicative examples of research projects on the impacts of drought on water quality deterioration

In France, the GICC-Seine project (Ducharne et al., 2005) has examined the hydrologic impacts of climate change in the **Seine River** basin. Ducharne et al. (2002) point out that the impact of climate change at the end of the 21st century is in general weak. Climate change induced a more contrasted seasonal river flow regime and more severe droughts are predicted. Climate change induces also an increase in nitrate fluxes in the soil toward aquifers, with concentrations that may exceed the level authorized to consider groundwater as potable water. Also in France, a new research project ICC-HYDROQUAL ("Impact of Climate Change on the Loire basin: HYDROlogy, thermal regime, water QUALity") has started in March 2009 for a two-year period. The objectives are to examine the evolution of the hydrological flow regime of the Loire river and its main tributaries as well as to analyze the consequences of climate evolution to the thermal river regime and the water quality (with a focus on water quality indices for assessing the good quality of water bodies involved in the European Water Framework Directive, i.e., nutrient concentration).

EUROLIMPACS, European Project to Evaluate Impacts of Global Change on Freshwater Ecosystems, (http://homepages.eawag.ch/~living/EU%20projects/eurolimpacs.htm) was another ambitious project with the objective to not just investigate stand alone impacts of change but to also consider impacts simultaneously such as changing land use and air pollution. Integrating climate change, land use change and atmospheric deposition is particularly challenging because of numerous process interactions and differing effects of all the driving variables. One such example is investigating the impacts of drought on hydrology and nitrogen. In this respect, the previous EU project INCA (Integrated Nitrogen Model for European Catchments) provided a sophisticated process-based flow and nitrate model that is applicable to all major European ecosystem types. Nitrogen in rivers originates from a variety of sources and is removed or converted to other forms of N via a range of processes. After severe droughts when nitrate mineralization is high, the subsequent breaking of the drought releases high nitrate loads into the river system. Nitrate peaks following drought periods have especially been of interest because of the effects of nitrate on the biological diversity of streams, and the requirement for public water supplies to meet EU water quality standards (Whitehead et al., 2005). Another worthwhile example is the role of drought in delaying recovery of Swedish streams from episodic acidification (Laudon, 2008).

The CLIMEX study in Norway (Wright and Jenkins, 2001) showed that mineralization of nitrogen may occur following high temperature periods and increase in CO2. In this study it caused a nitrogen sink to become a source.

Conversely, Evans et al. (2008) under the EUROLIMPACS project raised the importance of sulphate pulses in detrimentally affecting acid episodes due to oxidation of reduced sulphur held in organic soils, especially during more extreme summer droughts based on a 29 year observation period of a small, moorland stream in mid-Wales. Droughts can exacerbate acidification by creating lower water tables and fragmenting water courses (Dahm et al. 2003), aerobic conditions and increased oxidation of sulphur to sulphate (Wilby, 1994; Dillon et al. 1997).

Peat catchments contain significant stores of sulphur which have the possiblity of release during dry years (Aherne et al, 2006).

1.3. Soil – water interrelations

According to Resh (1988), the terrestrial features of an aquatic ecosystem include hill-slope landslides, riparian plant communities, and large animal impacts. This is in compliance with the definition of Integrated Water Resources Management (IWRM), which promotes the coordinated development and management of water, land and related resources. It is also well known that land use constitutes one of the factors influencing runoff and water quality at the watershed level. Deforestation of one piece of land for agricultural or urban development can affect local water balance and pollutant fate. It is therefore apparent how managing river basins in an integrated fashion is vital to buffer against the effects of drought on land-river aspects such as soil water, content, ephemeral water bodies, sediment transport and habitat suitability of biota. Hill and Polsky (2007) found that as water restrictions were imposed to combat drought effects in Massachusetts, building development continued worsening the availability of freshwater for public water supply during dry years. Long term planning and integration of land-use planning with water management were proposed as solutions to attenuate the impacts of urban growth and development.

Box 8 - Indicative example for research projects on the interaction between aquatic and terrestrial components

The environmental aspects of droughts were studied for the terrestrial impacts (MEDALUS, EFEDA, Desurvey). A key finding from work under MEDALUS and EFEDA was the inherent complex interaction between water availability and resilience of semi-arid ecosystems affected by drought. Experiments and field research indicated that at different temporal and spatial scales, different factors determine the resilience of terrestrial ecosystems to drought, including water redistribution, fire and grazing (Kirkby et al., 1996, Bergkamp, 1998). In the Nestos and Mornos Basins in Greece drought impacts were most noticeable on streamflow reduction and the knock on reduction in agricultural production. In the Nestos Basin the wetland ecosystem was impacts and biodiversity loss was observed (MEDA Water, 2007).

1.3.1. Soil water deficiency

Soil, as part of the soil – water – plant growing system is vital for land and water management, ranging from agriculture to urban growth areas and the construction industry (clay soils swelling and shrinking, reduction of soil stability, drying of organic matter in soils). This will reduce soil fertility and therefore biodiversity. Reduced soil structure also reduces water holding capacity and may increase the risk of erosion, especially where higher wind speeds occur during drought. This is especially true where wildfires occur during drought events (Bellot et al., 2001), and during re-growth post fire when heavy rain events may wash fine soil sediment and nutrients into watercourses, affecting water quality (Blake et al., 2009). The impact of soil drying and possible longer term reduced soil fertility on different and neighbouring habitats is not well understood during drought periods, especially on fragile habitats (e.g. chalk grasslands).

Drought conditions alter the structure of agricultural soils, drying certain soils into root impenetrable structures, exacerbating the effects of drought on certain vegetation. Harsh grazing of grasslands during drought can have detrimental effects on soil moisture stored in the shallow soil horizon, and may contribute to higher rates of upward flux where the groundwater is shallow (Anderson, 2008). Grass species will need to be taken into account with those most suitable to drought conditions preferred.

Corti et al., (2009) demonstrate through modelling that drought can cause significant infrastructure damage to buildings due to soil shrinkage as soil moisture is lost and groundwater declines in extreme events. They highlight that subsidence as a consequence of drought is difficult to determine due to the length of period of soil drying time and is often not visually evident on the soil surface. The effects of drought induced subsidence are difficult to model and predict as for floods and other natural disasters due to the slow and non-visible nature of subsidence. Salagnac (2007) showed that after the 1989 drought in France tens of thousands of residential buildings were affected by drought induced subsidence, and as a consequence soil subsidence was integrated in the French natural catastrophes insurance system (Cat-Nat). In 2003 the amount of drought induced subsidence damage peaked following the summer drought when up to 1000 million Euro of damage may have occurred (CCR, 2007).

Várallyay, (2009) summarised that water is a distinguished stress factor of soils and ecosystems. The description and analysis of positive or negative soil-water stresses are the preconditions of the efficient control of their mechanisms, reversible and/or irreversible consequences. The most significant soil-water stress is extreme moisture regime: water surplus (flood, water-logging, over-moistening) or water deficiency (drought). Their main reasons are the irregular atmospheric precipitation; limited water infiltration into and storage within the soil; high evaporation, surface runoff and filtration losses. In addition to the direct impacts the consequences are the changes in the mass and energy regime of soils and in their biogeochemical cycles. The possibilities of the control of soil-water stress are: to help infiltration, to improve the storage and availability of soil water; to improve plant water uptake; and irrigation and drainage.

On the other hand, high levels of soil organic carbon improve nutrient and water use efficiency, reduce nutrient loss and subsequently increase crop production (Dahm et al., 2003). Better infiltration and water retention in high organic carbon soils also increases water infiltration, reduces runoff and erosion and helps to avoid drought damage, thus contributing to the sustainability of food production (Trumper et al., 2009).

River operational plans should consider all these principles when addressing the impacts of droughts on aquatic biodiversity, and also on riparian vegetation. Shelterbelts, either designed or natural, offer species shelter and diversity of habitat, shade and weather protection (cooling effects), maintenance of soil and river bank stability and fertility, can help reduce wind velocities, dust (including air pollutants[4]) and erosion. Trees help filter pollutants and agricultural run-off as it enters the water environment, and provide an aesthetically pleasing environment (Bird, et al., 1992; Bird, 1998; Heath, et al., 1999). Drought can weaken the resilience of intact shelterbelts and larger forest ecosystems to pests and disease (Anderson, 2008). Maintaining flows for the environment into river operational plans should take into account the benefit healthy flowing rivers bring along the entire river course as a conveyance mechanism, and not just at point source extraction nodes for more ‘economically advantageous’ uses.

1.3.2. Desertification

Droughts do increase the possibility of desertification if the carrying capacity of non-irrigated land is exceeded. Well-managed land can recover from the effects of drought. Combining drought with land abuse sets the stage for desertification. Desertification became well known in the 1930's, when parts of the Great Plains in the United States turned into the "Dust Bowl" as a result of drought and poor practices in farming, although the term itself was not used until almost 1950.

[4] Increased dust and poorer air quality, especially in urban areas will likely affect older people and those with respiratory illnesses (Greater London Authority, 2008).

It is a misconception that droughts cause desertification. Droughts are common in arid and semiarid lands. Well-managed lands can recover from drought when the rains return.

1.3.3. Sediment transport in Rivers and Reservoirs

With reduced flow, transport of fine particulate stops with risk of accumulation, on the riverbeds within the interstices of the substrate, in pools and in reservoirs. These deposits may reduce the quality of fish habitat and cause significant changes in the ecosystem (Wood and Petts, 1999). The accumulation of organic matter and sediment may be flushed with the arrival of heavy rains and floods or released gradually when the drought breaks along the river network. This could be one possible post-drought effect that may affect ecosystem and limit its ability to recover. Increases in ammonium concentration due to sediment release during droughts were previously demonstrated by e.g. Mulholland et al., 1997 and Porter et al., 1996.

1.4. Key challenges from a science perspective

- The influence of land use on runoff and water quality is difficult to quantify, especially over the long term and at large scale such as that of a regional watershed where complex interactions occur (Quilbé et al., 2008). Yet, the scope of water management in droughts should be wider as so to relate with other European thematic priorities like common policy and economy of agriculture. For example, wetland creation and enhancement can in appropriate circumstances offer sustainable, cost-effective and socially acceptable mechanisms for helping to achieve the environmental objectives of the Water Framework Directive. In particular, wetlands can help to abate pollution impacts, contribute to mitigating the effects of droughts and floods, help to achieve sustainable coastal management and to promote groundwater re-charge (European Commission, 2003)

- Pyrce (2004) has discussed the use of different hydrological indices characterizing low flow regimes as "environmental flows". It is not clear yet which are the most relevant variables to preserve water quality and aquatic habitat. In particular, why selecting the annual minimum monthly flow with a return period of 5 years (in France), rather than the most widely used 7Q10 and Q95 flow? What is the reasoning behind this choice? An important question is to examine the use of these indices. This aspect should be investigated in a water management perspective, including other variables (e.g., temperature).

- There is the need to extend the knowledge on the combined effects of for instance simultaneous drought and high temperatures and their effects on all important water quality parameters. Caissie (2006) and Webb et al. (2008) review recent researches conducted on thermal behaviour of rivers. They note a renewed interest in this domain and propose that this could be partly due to the improvement of river temperature measurements. These data are indeed of great importance to investigate long-term variations in water temperature and their interactions with climate (air temperature, climate indices, solar radiation, etc.), river flow regime (discharge, groundwater inflow, etc.) and human activities (power generation, agricultural practices, release of heated effluent, reservoir operations, etc.). From these two reviews, several directions for future works are listed:

- detecting changes in time series observed in the past and attributing cause and effect to observed changes;
- investigating the key processes that govern water temperature evolution;
- modelling for human impact mitigation.

- As suggested by Johnson (2003), "more research is needed to examine under what conditions the stream temperature along the length of a river is influenced by fine-scale point processes versus upstream landscape-scale environmental conditions." This means that intensive field experiments are required to clarify the contribution of each energy flux influencing stream temperature dynamics in the past and for the future. Results of these experimental works might help to improve modelling by selecting and introducing the most relevant variables in the structure equations to be solved and to corroborate the possible causes of changes detected in time series. They might also contribute to identify uncertainties when models (from empirical to physically-based models that resolve the heat budget equation at local scale, as well as from stochastic to deterministic models) are used for predicting air temperature under global change scenarios. One major question to be addressed is to quantify the evolution of river stream temperatures in response to the probable increase in drought occurrence and in air temperature during the 21st century. As for GCMs and hydrological models, water temperature models are calibrated in the past conditions and results for the future thermal regime are obtained by extrapolation. In this context, how to be confident in the predictions?

- With still lacking understanding on ecosystem sensitivity, required flow conditions and the missing knowledge how future climate change will worsen the water quality deterioration in the Mediterranean, it is also impossible to asses the consequences of a drought management and short term activities, such as shortening of reservoir releases on the ecosystem functioning. So both aspects the missing indicators as well as the missing capability to assess consequences prevent a true integration of drought management plans within the WFD. In this context, a framework for the development of groundwater management strategies to maintain wetlands represents an important contribution that the Ramsar Convention Secretariat has provided in terms of methodology to fill the knowledge gap. This framework suggests the inclusion of groundwater-related management actions and strategies in the land and water management plan for the basin. Groundwater may be the most important water source for a wetland at particular times of the year, such as the dry season or during periods of drought. When the wetland is not at risk during wet periods, higher abstraction may be permitted in order to offset reduced abstraction when the wetland is in critical need. Most notably, the framework proposes to develop a conceptual model of groundwater-wetland interactions, to assess the situation of the combined impacts of abstractions, status and trends, and to determine the groundwater requirements of the wetlands. As groundwater discharge could be higher in droughts, water balances should be calculated for both the long term average natural conditions and for extremes (Ramsar, 2005).

- It has been suggested that using wetlands to manage droughts in a manner compatible with WFD objectives could assist Member States with implementation and integration of River Basin Management Plans. The list of pressures with potentially significant impacts on the hydro-morphology of water bodies includes traditional ‘hard’ engineering solutions that may prove unsustainable in the long-term on the scale necessary to support people, property and the environment. In the context of increased population growth and accelerating climate change, the role which wetland creation can play in offering alternatives to such ‘hard’ solutions is increasingly recognised, as illustrated in the case of water retention zones being restored in the Netherlands to mitigate the effects of both floods and droughts (European Commission, 2003).

2. Impacts on ecosystems

Every ecosystem has many levels of organization, for instance: system size; habitat structural characteristics (i.e. diversity, quality, quantity in terms of animal use); up- to downstream gradient of increasing discharge, increasing channel size, and decreasing substrate size; and physiochemical and biotic compositional properties. In terms of physicochemical properties, however, the levels of organization can be further scaled down, for example: coarse, fine, and colloidal inorganic particles; water chemistry; gaseous composition; coarse and fine particulate organic matter; and dissolved organic matter.

The abiotic environment as described by hydrological, geomorphological, and water quality characteristics, is one of the the steering factors for river ecosystem functioning. The biotic ecosystem functioning reflects the abiotic gradient and is described by functional and structural characteristics such as flux of matter and abundance of indicator species, respectively (Lorenz et al., 2001). The different abiotic and biotic factors may all influence the effects of drought impacts on a catchment.

Resh et al. (1988) have developed a schematic representation of the basic climatic and biogeochemical characteristics to assess disturbance regimes in the context of these factors (Figure below). The climate of any aquatic ecosystem can be depicted as having three basic features: light and temperature regimes, atmospheric chemical cycles, and precipitation. The climate and geology of the region in turn combine to control the hydrologic, geomorphic, and geochemical character of the system. The resulting geomorphic, chemical (both water and soil), and terrestrial features of catchments, along with local and regional land use, influence biotic structure and function of the water body. Timber harvest and road construction are two of many possible examples of detrimental land management.

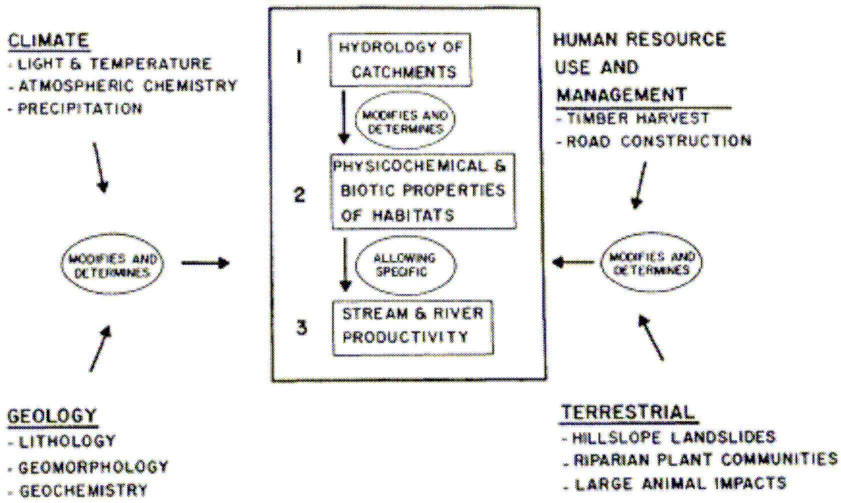

Figure: Representation of abiotic and biotic factors affecting stream productivity within a catchment (Resh et al., 1988)

Droughts are natural phenomena and many aquatic organisms regularly exposed to drought have evolved means to face the hydrological deficit (e.g. seek refuge from disturbance, develop physiological tolerance, etc.). During the most severe drought events or unpredictable drought events or an abnormal succession of droughts (supra-seasonal droughts), ecosystem may experience unusual physical conditions. In particular, pollutant concentrations and water temperature can be out of the range of acceptable values that can be tolerated by freshwater organisms, such as cold-water fish species, and fragile ecosystems can be at risk.

2.1. Biological conditions - The natural environment

Drought has both direct and indirect effects on stream ecosystems, in particular on all inputs and outputs that are dependent upon discharge, e.g., dissolved and particulate organic matter. Direct effects include loss of water, loss of habitat for aquatic organisms and loss of stream connectivity. Hydrological connectivity is disrupted ranging from flow reduction to complete loss of surface water. The longitudinal patterns along streams as to where flow ceases and drying up occurs differ between streams. The three patterns so outlined are 'downstream drying', 'headwater drying' and 'mid-reach drying'. Indirect effects include the deterioration of water quality, alteration of food resources, and changes in the strength and structure of inter-specific interactions. In addition, droughts have marked effects on the densities and size- or age-structure of populations, on community composition and diversity as well as on ecosystem processes (Lake, 2003).

When a drought sets in, surface runoff declines and also groundwater inputs also to water bodies diminish from the water table. At the same time, loss of water from evaporation and transpiration may increase due to accompanying high temperatures and often high winds. Thus, as a disturbance, drought's primary force is the steady loss of water at a large landscape scale. The steady water deficit thus generated differs in terms of flows for lotic systems as opposed to volumes and water levels in lentic systems. Streams to fall in level, shrink in length and cease to flow. Standing water bodies may shrink in volume and in surface area and may even dry out depending on size and depth. Estuaries with diminished freshwater inputs may increase in salinity and salinity may extend into upriver sections (Lake, 2008).

Natural terrestrial ecosystems and agrosystems are also affected by drought. Plant productivity is lowered because of water limitation until the very plant survival is threatened by water stress. Transpiration may increase, especially in forests, as well as pest and pathogen outbreaks. Plant species may change, being substituted by others with lower water requirements, with consequences for species interactions. There will be thus changes at the community level. For example, trees will be replaced by shrubs and eventually grasses should the drought be prolonged. Desertification may increase, triggering a positive feedback process. Fire risk as a result of a greater dryness of fuel materials such as wood, plant litter, etc. will be increasing as well. In agrosystems, as the water needs of crops increase, deficit irrigation will have to be supplied. Livestock are affected because thirst increases and feed items (fodder, grass, etc) are also diminished locally. Experiences in Australia are being closely observed in California concerning improving agricultural resilience to drought. Key lessons suggest that only the most innovative and efficient farmers are able to cope and manage drought years, and large storage in river basins is no guarantee of reliable or predictable water supply as it creates an artificially inexpensive source of water that is perceived as reliable and secure (Cooley et al., 2009).

Box 9 - Indicative examples of research projects on the impacts of drought on biodiversity

Integrating freshwater ecosystem conservation and water resources management

The Healthy Water Ecosystem research theme of Australia's Water for a Healthy Country Flagship Initiative aims to understand the key components driving the health of water ecosystems, material fluxes, and their response to disturbance and management as well as ecosystem responses to flows and water and habitat quality. Focused in the catchments of the Great Barrier Reef and the Murray-Darling Basin, this programme also aims to study the social systems affecting or benefiting from water ecosystems, economic drivers and outcomes and policy and planning systems. The Healthy Water Ecosystem research theme focuses on freshwater, estuarine and near coastal ecosystems and includes terrestrial systems dependent on surface and groundwater-dependent ecosystems. This is in accordance to the perspective of broadening conservation priorities and redefining freshwater protected areas in light of the widespread presence of human settlements in most catchments.

A similar process has involved Global Wetlands and Rivers Expert Group, also known as Skukuza Group. The previous two meetings of the Skukuza Group focused on better methods for selecting freshwater habitats for conservation (2004) and better conservation methods for conservation of freshwater biodiversity in protected areas (2006).

Concise classification of species according to their sensitivity to drought or to environmental features linked to drought

Only a few site prioritisation methodologies have been developed specifically to inland waters, e.g. the criteria used to identify Wetlands of International Importance under the Ramsar Convention. In response to this lack, the Freshwater Biodiversity Assessment Programme of the International Union for Conservation of Nature (IUCN) has initiated a project to review existing methodologies and develop assessment tools that identify potential effects of climate change on species including drought. Particular focus must be on vulnerable species and ecosystems, because these will probably be the first to be seriously affected by drought.

In terrestrial natural ecosystems, ecotones, "island" environments such as high mountain areas, gypsum and serpentine habitats, etc. and forests whose Southern distribution boundary is on the higher mountain tops are the most vulnerable to drought. In agrosystems, dry and irrigation farming and olive groves are at risk. In aquatic ecosystems, this is the case for endorheic environments, groundwater-dependent ecosystems, high mountain sites and coastal wetlands depending upon inland flows.

According to the site prioritisation method for conservation of freshwater biodiversity, one of the selection criteria is to pinpoint areas that are known or thought to be critical for any life history stage of a species. Examples of such sites may include: feeding grounds or stopover sites for migratory birds; migration routes for diadromous fishes; spawning, nursery and feeding areas; and refugia from adverse environmental conditions such as drought or pollution (Darwell and Vié, 2005).

2.1.1. Impacts of droughts on flowing water ecosystems

Bond et al. (2008) describe the effects of drought on naturally flowing streams as depending on many factors, including: rainfall patterns, the amount of water entering the stream especially from below-ground sources, groundwater levels, and the nature of the stream bed.

As water levels drop in the stream channel, there are progressive consequences. First the water shrinks away from the riparian zone, i.e. the riverbank, then from the littoral zone i.e. the river or stream edges where plants take root, and finally from backwaters. Lateral connectivity between the river and the backwaters and banks, and the floodplain beyond thus begins to weaken until it breaks. This can result in considerable loss of habitat (Elliott, 2006) and reduced inputs of organic matter, both living and detrital (Lake, 2008).

If the stream flow enters an extended period of low flow, consequences worsen. With less shade from riverbank vegetation and high air temperatures, the water temperatures rise. Populations of macroinvertebrates which maintain water quality by processing organic matter and also constitute fish food are reduced. Fish become stressed and their growth and reproductive success may be affected while some individuals begin to die. Streams that are fed by groundwater baseflow that is relatively rich in nutrients such as nitrogen and phosphorus but no longer benefit from the usual volume of upstream flow to dilute the nutrients, are liable to suffer from proliferation of filamentous algae.

Large floodplain rivers that would normally flood in the wet season, thus refilling and refreshing the floodplain wetlands, do not under drought conditions (Welcomme, 1986). When seasonal flooding is prevented for long durations like decades, the invertebrate egg bank gets depleted and booms compromised. Low water levels combined with loss of the usual seasonal flow patterns that trigger fish spawning, also inhibit recruitment in fish populations - i.e. there are few or no young fish. Oxbow lakes that depend on the flooding slowly drain and evaporate away, and as the water shrinks the concentration of oxygen in the water diminishes (Matthews, 1998) while salinity and temperature rise (Caruso, 2002), leading ultimately to fish kills.

As drought continues, water may stop flowing altogether. At this stage, the 'cease-to-flow' threshold is said to be crossed and the shallow areas - or 'riffles' - dry up (Stanley et al., 1997). These sections typically have well oxygenated shallow water when the stream is flowing. As the riffles dry up, fish and invertebrates tend to congregate in pools in deeper parts of the stream channel. With no flow linking the pools, the normal through-transport of nutrients, biota and organic matter stops. With time, the conditions in the river pools will change as each pool becomes a separate standing-water environment, more subject to conditions in its surroundings, above and below ground.

2.1.1.1. Temporary and ephemeral streams

Temporary streams represent a distinct class of water bodies (Gómez et al., 2005) and ecosystems with unique ecological importance (Doering et al., 2007). For the Mediterranean region, they are as important within the implementation of the WFD as the perennial water bodies for the more humid river basins of Europe. As variability of hydrological processes at local scale is widely accepted to be one of the most important factors driving species composition (Boulton, 2003; Pires and Coelho, 2000) and ecosystem functioning, it is important also to understand local hydrological variability and to take into account the variability of different temporary streams for the morphological and geological conditions across Southern Europe. The hydrological characterisation of temporary streams, in combination with the study of extreme events, is a central element of the projects tempQsim and MIRAGE.

Box 10 - Indicative examples of research projects on temporary streams

In this context, the European Commission has recently funded a research project entitled “Evaluation and improvement of water quality models for application to temporary waters in Southern European catchments (tempQsim)”.

Specific aspects on water quality dynamics in temporary streams have been studied during the tempQsim project and provide relevant background information for future impacts in the Southern European Countries.

The research project Mediterranean Intermittent River ManAGEment (MIRAGE) aims to provide specific key knowledge for a better assessment of ecological integrity (or ecological status in the words of the European Water Framework Directive) in Mediterranean temporary streams. The project derives a hydrological characterisation of temporary streams for the Mediterranean region, and provides an applicable set of reference conditions related to the specific ecosystem dynamics of temporary streams in the Mediterranean region based on the tight link between terrestrial and aquatic states (both structural and functional approaches). It assesses the effect of dry periods on the accumulation and transformation of nutrients, sediments and hazardous substances on the land and in river channels and supports the achievement of good ecological status as requested in the EU WFD and to make recommendations for integrative catchment management for both floods and drought periods.

For seasonal streams with winter flows and summer dry periods, drought may leave no detectable effect on biota. Much of the aquatic biota of ephemeral systems such as claypans or temporary ponds possesses desiccation-resistant propagules that may survive for decades (Williams, 2006). Although Acuña et al., (2005) found that drought caused significant changes in macroinvertebrate density on cobbles and leaves, but not on sand, and that in general few taxa resisted drying, and resilience to drying was the dominant response to disturbance in the Fuirosos, an intermittent forested Mediterranean stream. In the case of, severe drought, however, winter flows may be greatly reduced and the length of the summer dry periods extended, leading to subsequent losses of fauna when flow returns (Boulton and Lake, 1992a, b). Saline groundwater is also a problem in many coastal areas.

Riparian plants and trees that depend on groundwater may show stress if fresh surface water is absent for long than usual period (See Box 10)

Box 11 - Indicative examples of the impacts of drought events on terrestrial and aquatic ecosystems

Drought impacts on river red gum forests in the Murray-Darling Basin, Australia

Even robust trees at the streamside or on the floodplain, such as Australian river red gum (Eucalyptus camaldulensis) or black box (Eucalyptus largiflorens), eventually become stressed and die when prolonged drought prevents them from being flooded. River red gum is a tree species of high ecological significance to Australian floodplain rivers but already under enormous stress in many places along the Murray-Darling system. The poor condition of river red gums reflects long periods of alteration to natural river flows as well as the effects of salinity (George, 2005).

Lack of natural flooding to these forests of river red gum can cause irreversible loss of whole stands, as well as having major impacts on many other plants and riverine animals, including water birds. Red gums forests and other wetlands rely on a certain amount of wetland terrain that must be inundated periodically to sustain biodiversity and associated values (Bond et al., 2008) For example, flooding regimes are particularly important for the survival of egrets. Egrets generally breed in flooded forests though feed away from the nesting sites in more open wetlands. Egrets take longer than other water birds to commence breeding after flooding, and do not breed successfully unless their nesting sites are flooded for three to five months. This is thought to prevent terrestrial predators from accessing the nests (VEAC, 2006).

Moreover, water full of river red gum leaves become hypoxic, with decreased pH and fairly high concentrations of tannin and lignin. The presence of toxic wood leachetes from drought-induced litter and low oxygen availability in flooded river red gum forests may make these habitats unsuitable as nursery areas for native fish (Gerhke et al., 1993). It seems likely that increasing length and severity of drought may further increase the incidence of gum leaf invertebrate pest outbreaks such as gum leaf skelotoniser. This is a defoliating insect native to Eastern Australia whose action is added to the baseline leaf fall due to drought (VEAC, 2006).

One commonality among ephemeral streams is that perennial pools or sections of perennial flow sustain the majority of biodiversity and relatively few species are specialized to use other refuge types. For freshwater algae, drought refuges include perennial pools on streams and also desiccation tolerant dry biofilm on the streambed. Stream regulation increases algal dependence on dry biofilm but perennial pools are not required for successful recovery of algae after dry periods. Freshwater plants rely on a desiccation resistant seed bank that can be as long-lived as decades. Freshwater animals use refuges such as perennial pools, aestivation, adult flight and desiccation resistant eggs (Robson, 2008).

2.1.1.2. *Transitional waters*

By greatly lowering the freshwater inputs of estuaries, drought can induce major changes in the biota and in the trophic structure of estuaries. Droughts can have a strong impact on estuaries and their biota. With the reduction of freshwater inputs and the advance upstream of high salinity, there can be marked declines in abundance and seaward distribution of upper-estuarine freshwater biota, whereas the abundance of marine animals, such as crabs and shrimps, may increase in abundance within the estuary. Also phytoplankton and zooplankton may decline with the drought-induced decrease in the freshwater inputs of nutrients (Lake, 2008).

Box 12 - Indicative example of the effects of drought on estuaries

In a south Florida estuary, turbidity greatly declined with drought allowing greater light penetration into the water that increased primary productivity. This pulse of high productivity served to increase the biomass of herbivores, omnivores, primary and secondary carnivores, but not tertiary carnivores. The tertiary carnivores, many of which were basically freshwater fish were probably excluded from the estuary because of the high and stable salinity (Livingston et al., 1997).

2.1.1.3. Impacts of droughts on heavily modified and artificial water bodies

Urban aquatic habitats include urban streams, canals, rivers, ponds, impoundments, reservoirs and lakes and other water bodies that support aquatic life. These hydrological elements are however characterized by removal of natural vegetation drainage patterns, loss of natural depressions which temporarily store surface water; loss of rainfall absorbing capacity of soil and creation of impervious areas e.g. rooftops, and parking lots. In many cities, man-made drainage systems are instead typically provided through storm sewers, channels, and detention ponds. This is why aquatic habitats are included into the urban sewerage, playing a role of storm water receiver and disposer, and their structure is adapted for these purposes with canalization and damming.

The hydrological cycle in urban areas is significantly different in terms of smaller groundwater run-off, infiltration and recharge and lower water storage as opposed to surface runoff. Also through increased temperatures of effluents, reduced dilution of discharged pollutants, and changes in water bodies' morphology, drought can impact some of the main characteristics of aquatic habitats such as flow regime and chemical variables. Water quality decline and flow alternations, which are already particularly pronounced in urban catchments, are the primary factors of habitat deterioration to affect the performance of the associated biological communities in an urban environment (Lafont et al., 2007).

2.1.2. Impacts of droughts on standing water ecosystems

The changes to standing water conditions can cause severe stress to plants and animals that are more used to living in water that is flowing. Invertebrates, such as insect larvae, mollusks and crustaceans which feed by filtering food out of the flowing water, which were living in sections that have now become pools, noticeably disappear when the pool is isolated from flow. The assemblage of invertebrate fauna becomes more similar to that normally found in standing water bodies which is highly mobile, well adapted to severe conditions and largely made up of air-breathing predators such as hemipterans and coleopterans.

Permanent standing waterbodies - such as pools, wetlands and lakes - are generally fed by permanent inflow of water either from surface streams or from groundwater, with the volume being maintained by drainage or evaporation. As drought reduces the amount of water flowing into standing waterbodies without reducing evaporation, these shrink. Ephemeral or temporary standing waters, on the other hand, are fed by intermittent flows or rainfall, and the waters dry up in the absence of these sources. The omission of wet periods for temporary wetlands may result in the loss of biota and ecological functions that cannot persist for an abnormal period of dryness (Lake, 2008).

According to Bond et al. (2008), drought in standing waters can have major ecological effects, stressing and depleting both fauna and flora that inhabit them. Firstly, the part of the bed or channel that is normally at the edge of the water is left high and dry, stranding fauna such as mussels and rooted plants such as reeds (Brock et al., 2003; Furey et al., 2006). Secondly, the concentrations of salts and suspended solids in the water increase, and the dissolved oxygen concentration decreases. At the same time, water temperatures may rise depending on season, and the water would stratify into layers, particularly if very little water movement (Nowlin, 2004). Thirdly, nutrients (especially nitrogen and phosphorus) may be released from the sediments that form the bed of the waterbody, increasing the risk of algal blooms, particularly of toxic blue-green algae (De Groot and Van Wijck, 1993). This risk is especially higher in unshaded pools as the water level recedes from the normal shoreline with riparian and emergent vegetation (Lake, 2008). At the same time, decreases in inputs of dissolved organic carbon may lead to carbon limitation to microbial metabolism, resulting in autotrophic production being favoured over heterotrophic production (Humphries and Baldwin, 2003).

Longitudinal fragmentation of stream habitats prevents the normal transport of nutrients, biota and organic matter down river channels, often creating different conditions in each pool Not only may each pool become a distinctive lentic environment, but also the different layers within tend to have different characteristics of temperature, nutrient concentration and dissolved oxygen concentration. The combination of high temperatures and low oxygen levels may kill some species of fish and other fauna. Since natural disturbances such as droughts occur less often in the lentic benthos, differences in disturbance frequency may explain why biotic interactions seem to be much more evident in lentic than lotic communities (Resh et al., 1988)

When not depleted by stock watering or waterhole pumping, especially shaded, deep pools may persist throughout the drought. Others may dry up after a time, killing their inhabitants. The former are known as drought refuges, or refugia, because they are critical refuge habitats to the survival of many species in drought-prone rivers and wetlands. The characterization of flood refugia is much more advanced than that of drought refugia (Lake, 2000).

Box 13 - Indicative example of the indirect effects of drought on lake ecosystems

The position of lakes in the landscape may influence response to drought. Lakes high in their position in the hydrological flowpath were found to receive most of their water from precipitation rather than groundwater. Lakes, low in the landscape receive a considerable proportion of their inputs from groundwater. When drought occurs, an elevated lake tends to lose its input from precipitation while maintaining a groundwater outflow. On the contrary, a low lake will often continue to receive groundwater inputs during drought. This pattern of flows in the landscape results in the elevated lakes losing ions in favour of low lakes (Webster et al., 1996), with limitations to the distribution animals, such as crustaceans and molluscs, which have a high calcium requirement (Capelli and Magnuson, 1983; Kratz et al., 1997).

2.1.2.1. Wetland-reliant species in seasonally flooded areas

As part of the consequences of climate change, increasing drought events are projected to cause significant alterations to aquatic biogeochemical processes including carbon dynamics, aquatic food web structure, dynamics and biodiversity, primary and secondary production; and, affect the range, distribution and habitat quality/quantity of aquatic mammals and waterfowl. Projected effects on aquatic mammals and waterfowl include altered migration routes and timing; a possible increase in the incidence of mortality and decreased growth and productivity from disease and/or parasites; and, probable changes in habitat suitability and timing of availability (Wrona et al., 2006). Specifically, faunal change may occur with migratory and nomadic bird and fish species that use a network of wetland habitats across or within continents, respectively. These migratory as well as resident animals like amphibians may lose important staging, feeding and breeding grounds. The cross-continental migration of many birds is at risk of being disrupted due to the changes in the aquatic/terrestrial habitat ratio (Walther et al., 2002; Gómez-Rodríguez et al., 2009). Disruption of rainfall and flooding patterns across large areas of arid land will similarly adversely affect bird species that rely on a network of wetlands and lakes that are alternately or even episodically wet and fresh and drier and saline (Roshier et al., 2001; Johnson et al., 2005).

The scattered and isolated nature of many wetland systems in southern and central Europe may hinder the migration of wetland species to more suitable climatic conditions. In addition, drier conditions in the Mediterranean region may adversely affect the trans-Saharan migrant bird populations that rely on suitable foraging habitat whilst en-route. The same birds are also likely to suffer loss of their breeding habitats in northern Europe (Zöckler and Lysenko, 2000). These are important arguments in the debate on whether protected areas may be less effective in conserving biodiversity as climate change causes shifts in the distribution of species. These concerns highlight the need for regionally focused management approaches at the scale of landscapes such as, increasing the number and size of protected areas, providing 'stepping stones' between habitats and protected areas and restoring critical types of habitat, as well as ensuring that the current Important Bird Areas (IBA) network is adequately projected into the future (Bennune et al., 2005; Hole et al., 2009). Biodiversity climate change adaptation tools, such as flyways, buffer zones, corridors and stepping stones, enhance the coherence and interconnectivity in Europe (Kettunen et al., 2007).

2.1.3. Impacts of droughts on terrestrial ecosystems

Parmesan et al., (2000) have reported a few examples of the impacts of drought on terrestrial biota. Direct effects include the 1975–77 severe drought over California which caused the extinction of 5 out of 21 surveyed populations of Edith's Checkerspot butterfly (Ehrlich et al. 1980; Singer and Ehrlich 1979). It was also found that, for one particular finch species of Galapagos, wet years select for small individuals while droughts select for large ones, leading to frequent shifts in the distribution of body sizes (Boag and Grant 1984). An example of how droughts affect animal behaviour and reproduction comes from African elephants. In this species, breeding is year-round, but dominant males mate in the wet season and subordinate males breed in the dry season. Therefore, a change in the intensity or duration of the rainy versus drought seasons could change relative breeding rates and, hence, genetic structures in these populations (Poole, 1989; Rubenstein, 1992). Consequences of drought on population and community dynamics are also quite commonly studied. For example, a widespread drought in the 1987–88 caused simultaneous crashes of insect populations across the United States, affecting diverse taxa from butterflies to sawflies to grasshoppers (Hawkins and Holyoak, 1998). Conversely, drought can be related to population booms in other insects (e.g., certain beetles, aphids, and moths) (Mattson and Haack, 1987).

Weather and climate events qualify as extremes depending on duration and intensity. In addition to duration, the intensity of a drought can be measured largely by the ability of biota to tolerate the dry conditions. Although a drought may end abruptly with the return of adequate rainfall, the effects of a drought on the landscape and composing ecosystems may last for years. Severe droughts have been associated with regional-scale forest mortality worldwide and climate change is expected to exacerbate regional mortality events. However, prediction remains difficult because the physiological mechanisms underlying drought survival and mortality are poorly understood. McDowell et al. (2008) have developed a hydraulically based theory that allows analysis of survival and mortality mechanisms by considering carbon balance and insect resistance in the equation. The analysis is based on plant regulation of water use, which falls into two categories labelled isohydric and anisohydric regulation.

More generally, drought can lead to major episodes of tree mortality on land by initiating outbreaks of insects and disease in forests. These limitations to terrestrial ecosystems' productivity can hinder the ability to cycle essential geochemical elements (National Drought Policy Commission, 2001). Kelly and Goulden (2008) suggest that drought may contribute to rapid shifts in plant species location due to changing soil moisture regimes and insect attack using an example from Southern California. Observations from the Tyrol in Austria between 1994 and 2004 as part of the GLORIA observation network show a shift in certain species towards higher altitudes than normal. Species dwelling near mountain peaks were observed to decline as the temperature increased (Pauli et al., 2007). Pauli et al., (2009) suggest similar trends based on wider European observations. Paoletti et al., (2007) raise concern at the increasing susceptibility of forests to fire caused by air pollution. Elevated background levels of ozone and nitrogen deposition increase leaf turnover rates, as well as nitrogen and lignin content in needles. This reduces litter decomposition and increases fire fuel build-up. Ozone exposure and increased levels of nitrogen availability may also reduce root/shoot mass and plant control of water loss, therefore increasing tree susceptibility to drought stress and fire. Better understanding of mechanisms of air pollution effects on wild-land fires in forests and other terrestrial ecosystems is needed.

2.1.4. Interaction between terrestrial and aquatic ecosystems during drought

Water bodies interact with their terrestrial surroundings in the riparian zone, floodplain or the sedimentation area. In pools with stored organic matter such as dead leaves from streamside trees, the leaf contents will progressively leach into the water, and decay processes will use up dissolved oxygen. When drought stress on the trees causes more than usual leaf fall out of season, the dissolved organic matter in pools may be a significant hazard for the fauna (Bond et al., 2008). Increases in the frequency, duration, and/or severity of drought and heat stress associated with climate change could fundamentally alter the composition, structure, and biogeography of forests in many regions, with the potential for large carbon losses to exert feedback on climate change (Allen et al., 2009). Amazon forests appear vulnerable to increasing moisture stress (Phillips et al, 2009). Large quantities of soil carbon are lost due to the drainage of peatlands and further exacerbated by the increased likelihood of fire outbreak on these otherwise water-logged environments (Trumper et al., 2009).

Drying, oxidising and eroding peat adds sediment and colour to stream and river water which has to be removed at tap or dredged at the harbour, costing millions each year. In the UK, water companies are looking at peatland management as a proactive investment in water supply quality (Leadbitter, 2007). Although watercolour does not pose a public health issue, Chow et al., (2003) highlight that chlorination processes at water treatment plants generate trihalomethanes as by-products – and THMs are carcinogenic. Peatlands, bogs, mires and fens are generally the most vulnerable habitat types in Europe, with up to 50% negatively affected, yet they are extremely important habitats for a wide range of species, and critically they are carbon stores and their degradation releases greenhouse gases into the atmosphere (EEA, 2010).

The wider impact of drought on general ecosystem productivity has been reported by Cais et al., (2005). They reported measurements of ecosystem carbon dioxide fluxes, remotely sensed radiation absorbed by plants, and country-level crop yields taken during the European heatwave of 2003. Model results, corroborated by historical records of crop yields, suggest that such a reduction in Europe's primary productivity is unprecedented during the last century. An increase in future drought events could turn temperate ecosystems into carbon sources, contributing to positive carbon-climate feedbacks already anticipated in the tropics and at high latitudes.

In addition to drought, grassland ecosystems experience periodic invasions of insects or mammalian herbivores, late or early frosts, wet or cool years, hail, fire, and other perturbations. Because different species are likely to perform best for particular combinations of these disturbances, the long term stability of primary production in these grassland areas should depend on their biodiversity (Tilman and Downing, 1996).

Another important element of indirect drought impacts in relation to local forest dynamics is the increased frequency of fires. The risk of increased fire frequency arising from changes in drought magnitude could have implications for lakes and streams, which will receive greater, potentially toxic runoff immediately following fires (Arnell, 1999). In the Sierra Nevadas of California, fire frequency has sown to be correlated to fuel loads (related to trees species composition and age structure), temperature, and fuel moisture. Periods of drought followed by weeks of extreme heat and low humidity provide ideal conditions for fire, which are, ironically, often sparked by lightning associated with thunderstorms at the drought's end (Swetnam 1993; Stephenson and Parsons, 1993; Root and Willig, 2000).

Box 14 - Indicative examples of research projects on the impacts of drought on terrestrial ecosystems

Minimisation of and Adaptation to Climate change Impacts on biodiverSity (MACIS)

MACIS (www.macis-project.net) was a European Commision-supported project that reviewed observed and projected future changes in processes that affect biodiversity in Europe, concentrating on terrestrial ecosystems. It delivered - inter alia - a detailed report on adaptation and mitigation measures in different sectors and their impact on biodiversity in terms of fragmentation, degradation, over-exploitation and pollution of ecosystems.

Assessing LArge scale Risks for biodiversity with tested Methods (ALARM)

In the context of the ALARM Project (www.alarmproject.net), research has been carried out on the structure, function, and dynamics of a number of terrestrial and freshwater ecosystems and the changes in biodiversity due to risks arising from climate change, environmental chemicals, and biological invasions among others. In particular, 21 different studies have dealt with the effects of drought on above-ground biomass accumulation, mushroom production and soil enzyme activity in a Mediterranean holm oak forest, the mortality factor in Scots pine stands, or the photosynthetic performance of ericaceous shrub species, just to cite a few.

Biodiversity Requires Adaptation in Northwest Europe under a CHanging climate (BRANCH)

The BRANCH project (www.branchproject.org) has modelled the response of a number of species listed in the Annexes of the Birds and Habitats Directive that were cross-referenced with those Natura 2000 sites where these species are known to occur, The aim was to investigate the comparison between the projected distributions and determine where a net gain or net loss in habitat extension is likely to occur. The project looked at the correspondence between the location of 679 sites in France, the Netherlands, and United Kingdom and the projections for this species' future climate space, advocating change to spatial planning and land-use systems to allow wildlife to adapt to climate change.

2.2. Ecosystem vulnerability and resilience to drought

Resilience reflects the degree to which a complex adaptive system is capable of self-organization and the degree to which the system can build and increase the capacity for learning and adaptation. Self organization is opposed to lack of organization or organization forced by external factors.

Folke et al. (2004) have described the loss of resilience as through the combined and often synergistic effects of those pressures that can make ecosystems more vulnerable to changes whereas those could previously be absorbed. As a consequence of these pressures, ecosystems may suddenly shift from desired to less desired states in their capacity to sustain ecosystem services to society. In some cases, these shifts may be irreversible or too costly to reverse. Irreversibility is often the result of changes in variables with long turnover times such as biogeochemistry, hydrology, or climate. Irreversibility also depends on the loss of biological sources and on the interactions for renewal and reorganization of the ecosystem into desired states.

In light of the changes to ecological structures and functions and their implication for human well-being, the capacities for self-repair of ecosystems can no longer be taken for granted. Active adaptive management and governance of resilience will be required to help sustain or create desired states of ecosystems. A first step in this direction is to understand better the interactions between regime shifts, biological diversity, and ecosystem resilience (Folke et al., 2004).

Box 15 - Indicative examples of the multiple attributes of resilience from the latest studies

Latitude is the maximum amount the ecosystem can change before losing its ability to reorganize within the same state. Loss of trees in cloud forests is one such example where the regime shift may be moreover irreversible. In some mountainous areas, the forests were established under a wetter rainfall regime thousands of years previously. Necessary moisture is supplied through condensation of water from clouds intercepted by the canopy. If the trees are cut to such an extent that the water input stops, the resulting conditions can be too dry for recovery of the forest (Wilson and Agnew, 1992).

Precariousness is how close the current trajectory of the ecosystem is to a threshold that, if breached, makes reorganization difficult or impossible. Headwater peat-bogs are unique ecological communities in this sense. They can be destroyed in a matter of days, but require hundreds of years to form naturally (Krecek and Haigh, 2006).

Resistance is the ease or difficulty of changing an ecosystem. In trophic cascades, loss of top predators can increase the vulnerability of water bodies to eutrophication by excessive nutrient input (Carpenter, 2003). Also the vulnerability of other major functional groups can pose drastic risk to ecosystem functioning. Water bird guilds that feed on different trophic resources thus regulating the macrophytes/algal bloom balance are one such example. In this respect, the diversity of responses to environmental change among species that contribute to the same ecosystem function is particularly important. It is yet not clear whether the overall loss of biodiversity reduces the response diversity of species to change (Elmqvist et al., 2003). However, greater ecosystem resilience can be expected from greater diversity at different trophic levels.

Cross-scale relations is how the above three attributes are influenced by the states and dynamics of the (sub)-systems at scales above and below the scale of interest. These cross-scale aspects of resilience are captured in the notion of panarchy. A good example of how vulnerability to droughts is nested across scales is offered by the Murray-Darling River Basin in southeastern Australia. At the level of ecosystem functions, lack of the full suite of natural river flows may result in higher turbidity and less productivity. When water is not sufficient and summer freshes are delivered in isolation, ‘blackwater’ events may translate into darkly discoloured water associated with low dissolved oxygen and high organic matter (Atkinson et al., 2008) with consequences for aquatic species. At the biota level, Box 10 describes how failing to deliver environmental flows to iconic river red gum forests may result in irreversible loss of this vegetation type and associated riverine fauna and processes regulated by riparian vegetation (Pusey and Arthington, 2003). At the scale of the whole river basin, there are different risks to pose a serious jeopardy to future water resources availability, including plantation forestry, growth in groundwater use, bushfires, farm dams, and reduction in return flows from irrigation. Climate change and droughts in particular, have been identified to account for almost half of the estimated reductions in water volumes (Murray Darling Basin Commission, 2003).

2.2.1. Ecosystem thresholds and regime shifts

Droughts put aquatic biota under increasing stress through progressive loss of habitat, depletion of food resources and decline of water quality as well as increased likelihood of biotic interactions as flow reduces. As perturbations that occur over large spatial scales e.g. landscapes, droughts have the potential to threaten the survival, not only of individual aquatic organisms, but also of regional populations, or even species themselves In addition, change in drought frequency and magnitude influences the species composition and structure of ecosystems (Bond et al., 2008). Two aspects of biodiversity are distinguished when analysing the potential for reorganization: functional-group diversity and functional-response diversity. The diversity of functional groups in a dynamic ecosystem undergoing change, the diversity within species and populations, and the diversity of species in functional groups appear to be critical for resilience and the generation of ecosystem services. Perturbations such as prolonged drought can reduce the functional diversity of animal communities beyond changes in species richness alone, potentially imperilling provisioning of ecosystem services (Elmqvist et al., 2003).

The effects of drought on aquatic biota are most likely to be abrupt when geomorphological or hydrological thresholds are crossed, causing abrupt changes in biological community structure and ecosystem processes (Humphries and Baldwin, 2003).From a species perspective, ecosystem responses such as shifts in ecosystem or vegetation types imply changes in habitat quality and distribution. Finally, climate change in general is likely to facilitate the establishment of non-native invasive species through increased niche availability (Olofsson et al., 2008) although not all of them may be unwelcome from a resources perspective (National Drought Policy Commission, 2001).

Matthews and Marsh-Matthews (2003) have compiled a list of the phenomena related to fishes reported or predicted to be affected by drought, across increasing scales of organizational complexity, i.e. individuals, local populations, local assemblages, metapopulations, basin or regional faunas, effects of fish in ecosystems, Changes in invertebrate assemblages or biomass, and evolutionary effects. The most frequently demonstrated effects of drought appear to be population declines, loss of habitat, changes in the community, negative effects from changes in water quality, movement within catchments, and crowding of fish in reduced microhabitats. A study by Magalhães et al. (2007) showed that Mediterranean stream fish assemblages could be significantly affected by the occurrence of droughts, which caused changes in species relative abundances but had little impact on species richness, composition (persistence) and rank abundances (concordance). Therefore, longer and more severe droughts expected under altered future climates, may result in declines or local extinctions of the most sensitive species and their potential replacement by more resistant species.

Holling (1973) has defined resilience as the magnitude of disturbance that the system can experience before it shifts into a different state, namely a new stability domain. After the ecosystem has reorganized into a new structure, vital functions such as the provisioning and regulating services assume a different control over the ecosystem's structure. For example, the transition from a bog to fen environment will imply different performances in terms of water retention and flood mitigation (Charman, 2002; Haigh and Kilmartin, 2006). Available runoff and flood peaks will in turn activate a feedback loop on pH-dependant species composition. Walker et al. (2004) defined resilience as the capacity of a system to absorb disturbance and reorganize while undergoing change so as to retain essentially the same function, structure, identity, and feedbacks. If not, any shift from desired to less desired states may result in gradual loss of ecosystem resilience.

When climate conditions change beyond species' breadth of tolerance, species may be forced to respond by shifting the timing of life-cycle events (*phenology*), shifting their geographical boundaries (*range shift*), changing morphology, behaviour or their genetic makeup. Changes in seasonal timings will affect species' dependencies and reproductive success of species. Shifts in location of suitable "climate space" and the distribution of species, raising issues of suitability of habitat in new areas of climatic suitability. When neither adaptation nor shifting range is possible because population numbers are low, habitats are restricted or patchy, and climatic or geographic ranges are limited, *extinction* is a likely scenario (Rosenzweig et al., 2007). The cause behind the response can be either *plastic* (changes within individuals during their lifetimes) or *genetic* (changes in genotypes between generations and among populations) (Theurillat and Guisan, 2001; Parmesan and Matthews, 2006). the major impacts of drought on biodiversity may include, impacts of extreme weather events on species survival, changes in habitat composition and structure as species move northwards, including the expected increase in invasive species and diseases, impact of changing land use as agriculture, water, forestry and other countryside industries and interests adapt to climate change.

Box 16 - Indicative examples of demonstrated thresholds from the latest studies

Grass-dominated to shrub-dominated savannas

State changes occur in semi-arid rangeland systems where droughts, grazing and water tolerance of plant species interact to shift the system between grass or shrub dominance. Marked fluctuations in grass and woody plant biomass are a characteristic feature of savannas, because of the highly variable rainfall, and primary productivity from one year to the next. Herbivores cannot respond fast enough to track these fluctuations, and the accumulation of grass during wet periods means periodic accumulation of fuel and, therefore, fires. The net effect of fires is to maintain savanna rangelands in more open, grassy states.

The change to woody state of the grass/shrub-livestock system comes about through a combination of sustained grazing pressure and lack of fire. Overgrazing removes drought tolerant plants, and subsequent droughts with high stock numbers bring about the death of perennial grasses and lead to reduced grass cover. When followed by good rains, establishment of shrub seedlings occurs as these seedlings can get their roots below the grass-rooting zone to survive the first dry season. Species composition and tolerance to water stress determine vulnerability or resilience (Folke et al., 2004).

Sawgrass vegetation to cattail vegetation in Florida Everglades

The Everglades is an oligotrophic wetland that for the past 5,000 years has effectively self-organized around a low nutrient status, pulsed by annual wet/dry cycles and by decadal recycling associated with fires. The soil phosphorous content is the limiting factor that primarily defines two alternate states. Because of nutrient enrichment, the freshwater marshes shifted from wetland dominated by sawgrass to cattail marshes in the late 80s and early 70s. Several types of disturbances can have triggered such a switch between states, each type representing processes and structures that occur at different spatial and temporal scales. The vegetation structures represent the most rapidly changing variables, with plant turnover times on the order of 5–10 years. The disturbance regimes of fires operate on return frequencies of 10–20 years. Other disturbances such as freezes and droughts occur on multiple decade return times.

In this example from the Everglades, the loss of ecological resilience is related to the slowest variable in the system. Soil phosphorus concentrations have turnover times on the order of centuries. The original stability domain of sawgrass and wet prairies matrix was maintained by the interaction of fire, droughts and subsequent hydrologic regimes Disturbances like droughts and peat-removing fires were previously absorbed without a state change by the ecosystem. The gradual accretion of soil phosphorus in the marshes is responsible for having broken the equilibrium and triggered the change in vegetation (Gunderson, 2001).

2.2.1.1. Range shifts for species

For many species, habitat exists beyond their distributional limits that would be suitable but for climatic factors. In such cases, ranges are limited by climate. As the distance to the edge of the range for a species decreases, individuals often experience increasingly stressful climatological conditions resulting in fewer, smaller patches of suitable habitat, or in decreased reproduction. Thus, individuals living along range boundaries are often living at the edge of their species' physiological tolerances and thus are more likely than those living in the interior to experience stressful, harmful, or lethal weather events. Mounting evidence indicates that species are currently responding to twentieth century warming by shifting their ranges poleward and upward in altitude (Parrmesan et al., 2000). The BRANCH Project (See Box 13) found that some of the Natura 2000 sites are located within areas whose climate characteristics are projected to become unfavourable for species listed in the Habitat and Bird Directives.

2.2.2. *Refuge habitats*

Drought, like other forms of ecological disturbance, can remove some of the habitat areas that biota would normally use. The biota become thus restricted to isolated 'refuge habitats'. Refuge habitats, also known as refugia, take many forms and are found in many or all types of aquatic ecosystem. Sedell et al. (1990) have defined refugia as “habitats or environmental factors that convey spatial and temporal resistance and/or resilience to biotic communities impacted by biophysical disturbances”. Because drought has widespread ecological effects, the range of stream biota across a riverine network needs more than just ecologically high-quality types of refuge habitat. To survive, several species will use less ideal niches in any critical part of the network, even parts that are in need of ecological restoration. If not seeking refuge from disturbance, many aquatic organisms will also have adaptations (such as metabolic torpor, physiological tolerance of low oxygen levels or air-breathing from the surface) that provide refuge from the stress of stagnation (Kramer, 1987; Kramer and McClure, 1982; Magoulick and Kobza, 2003).

Refuges have in common that they support particular aquatic biota, or sustain some moisture during dry spells and drought, making the effects less severe. Waterholes, floodplain lagoons and riverine pools are commonly thought of as aquatic refuges in riverine landscapes. But there are also other refuges in both temporary and permanent streams. Examples include logs, wet patches under-banks, riffles, streambed sediments, yabby holes, riverside and riverbed vegetation. All of these can support freshwater species that do not have resistance traits, or need to sustain moisture in their habitats during dry spells and drought. In streams and rivers where normally permanent flows are being reduced or lost, streams, or sections therein that continue to flow are potentially important refuges. According to different longitudinal patterns of drying for streams as opposed to large rivers, such areas are more likely to be found in spring-fed streams which may persist in drought or in the larger downstream reaches of the river network that persist as pools or low flow streams. In other situations, both headwaters and downstream reaches may persist in drought and drying occurs in the heavily sedimented mid reaches (Lake, 2008).

The types of refuges that are important will depend on both the ecosystem type and the biota that need to use them. For example, in intermittent streams isolated pools where fauna are protected from desiccation are a key form of refuge, while in perennial streams that continue to flow throughout the drought, cool shaded gullies or areas receiving cool groundwater inputs may be important in protecting biota from thermal extremes (Bond, 2007). For macroinvertebrates, refugia may be a section of river upstream or downstream, within the hyporheic zone, or in the case of taxa with an aerial dispersal phase, recolonisation may occur from another river catchment (Wood and Petts, 1999). In aquatic systems, drought also leads to shifts in refugia spacing and connectance at multiple spatial and temporal scales (Magoulick and Kobza, 2003).

Drought produces a decrease in habitat area/volume and an increase in extremes of physical and chemical water quality parameters. These conditions are linked with biotic interactions such as competition and predation that structure the community of fishes residing in low-flow or dry season refugia by increasing mortality rates, decreasing birth rates and/or increasing migration rates. For example, resident fish populations will be competing to survive in less and less water, making them more vulnerable to their predators, including other fish and waterbirds or land-based predators. In pools with high densities of trapped fauna the levels of parasitism and disease, notably of fish, can rise. As an example of indirect disturbance during drought, small-bodied fish may seek refuge from adverse biotic interactions in rather shallow holes that do not harbour large-bodied predators (Magoulick and Kobza, 2003).

Box 17 - Indicative examples of refuge habitats from the latest studies

Groundwater-dependent fish species

Due to its relatively long response times to rainfall surplus or deficit, groundwater is the best buffered portion of the hydrologic cycle. As such, groundwater is ecologically significant both in terms of contribution to river baseflow and physiological refuges. This is especially the case in the upper coastal plain areas of watersheds where the aquifers are shallow and flowing springs are common. For example, the Floridian Aquifer underlies most of the coastal plain portion of the Altamaha River in Georgia, USA. Here, most of the baseflow is derived from groundwater sources during droughts. Although the area and amount of groundwater input to the Altamaha River, its tributaries and its estuaries have been substantially reduced as a result of intensive withdrawals, many economically and ecologically important fish species rely on sites where groundwater upwelling still occurs during periods of physiological stress like droughts. One of the best example of such dependence on groundwater-sustained refugia is the short-nose sturgeon and the Atlantic sturgeon (Shaw, 2001).

Limiting factors in streams and pools for trout during drought

Summer droughts are a regular feature of most streams where trout live. However, the severity of drought episodes varies considerably. Severe droughts reduce the volume of instream water available to trout and thereby force them into pools. Hakala and Hartman (2004) studied brook trout populations in forested headwater streams of West Virigina. They found that reductions in fish density and population condition during, and in the-post drought period, were related to spatially-limited food resources and/or increased fine sediment levels, but not to degraded water quality.

When streams dry up during severe summer droughts, pools are essential for salmonid survival. However, survival largely depends upon suitable temperature and oxygen concentrations being available in each pool. It is also difficult to separate the direct effects of a drought in a hot summer from the effects of high air temperatures. A study on the English Lake District by Elliot (2000) found that not all the pools containing brown trout in non-drought years serve as refugia for this fish. This is because the trout have to cope with adverse water quality, especially increasing water temperature and decreasing oxygen concentration. Even in the larger pools serving as refugia, the trout do not occur at all depths but show a preference for the cooler water near the bottom. This is despite the oxygen concentration is lower than that near the surface. In fact, the trout showed clear preferences for certain combinations of temperature and oxygen concentration.

2.2.3. Ecological responses to drought

According to Lake (2003), drought as a perturbation consists of two parts: the disturbance (i.e. the impacts of the decline in water availability), and the biotic responses to the disturbance. In disturbance ecology, there is general agreement that biota may react either by resistance or by resilience. Native species of arid-zone rivers have been exposed to countless droughts over the millennia. These biota usually possess adaptations which allow them to survive the drought by 'sitting it out', and to recolonise and recruit in affected areas after the drought breaks. Biota that 'sit the drought out' manage to do so either thanks to desiccation-resistant life-history stages or by making use of remnant habitats offering less harsh conditions in the otherwise drought-affected environment. Resistance is therefore the capacity of the biota to withstand and persist through the drought. On the other hand, resilient species have evolved traits that enable them to effectively recover from drought after suffering its impacts (Lake, 2008). These are well developed mechanisms that allow widespread and rapid dispersal between suitable patches of habitat, and capacity for rapid breeding once there (Adams et al., 2005).

Davey and Kelly (2007) found that resilience rather than resistance is key to the persistence of mobile animals in environments that suffer catastrophic disturbance over large areas such as drought. By studying how the position of refugia along a stream that is intermittent in its middle reaches, they also found that the spatial position of refugia within the landscape is likely to play a critical role in shaping biological responses to disturbance events in such systems. In the upper river, fish migrated upstream to permanent water as the stream dried from the bottom up. However, frequent drying and slow recolonization by most species combined to produce a fish community in intermittent reaches that was quantitatively and qualitatively different to that in neighbouring perennial reaches. In the lower river, fish did not appear to migrate downstream to permanent water as the stream dried from the top down. Nevertheless, a lower frequency of drying episodes and faster recolonization by selected species from downstream refugia allowed fish community structure to recover fully during prolonged wetted periods.

Box 18 - Indicative examples of ecological responses to drought from the latest studies

Resistance and resilience strategies in fish species of Florida Everglades

In the marshes of southern Florida, two species of the same genus react differently to drought and the low water quality resulting from formation of small isolated patches. Fundulus chrysotus shows resistance to the low water quality conditions of the “drydown” by persisting in low numbers, whereas adults of Fundulus confluentus spawn along the peripheries of the pools as they dry up and their eggs are then left on dry ground to hatch once rewetting occur (Kushlan, 1973). For many biota, dealing with disturbance entails a combination of resistance and resilience. For example, the eastern mosquitofish Gambusia holbrooki of Florida Everglades can tolerate the poor conditions in drying pools and when high water levels return, it rapidly disperses into newly inundated habitat, reproduces and rapidly builds up high population numbers (Ruetz et al., 2005).

Traits and adaptations to stranding of littoral benthic macroinvertebrates

Another example of resistance to drought conditions comes from immobile biota, such as attached algae and macrophytes, molluscs and oligochaetes. Furey et al. (2006) compared the littoral invertebrate fauna of a reservoir wherein numerous level changes occurred with that of a nearby stable lake. They found that the fauna of the drawdown exposure zone of the reservoir was greater in density and biomass than that of the stable lake. They suggest that the reservoir shore fauna with r-selected survival strategies is well adapted to drawdowns, such as occur in droughts. Traits of emersion-tolerant species of freshwater bivalves include the uptake of aerial oxygen, careful control of valve movement, and the use of calcium to buffer haemolymph acidosis (Byrne and McMahon, 1994; Gagnon et al., 2004).

According to the theory of metapopulation dynamics, temporary wetland organisms can adopt two strategies to cope with the periodic drying of their habitats. The first is related to active migration or dispersal, i.e. escape in space, and frequently involves a winged adult stage which allows evading drawdown situations by seeking refuge in other water bodies. These species are called ‘‘true dispersers”. The second strategy is related to escape drought in time. Many organisms have limited active dispersal form drought-resistant life history stages such as dormant plant seeds and diapausing invertebrate resting eggs which aestivate in the dry sediment. These species will emerge into the water column as soon as temporary habitats refill and are termed ‘‘true residents’’. Others may disperse actively and enter an ovarian diapause in terrestrial soils or vegetation, or can remain active in the uplands until wetlands refill. Because such organisms frequently have a high site fidelity they can be qualified as ‘‘resident dispersers’’ (Brock et al., 2003; Angeler and Alvarez-Cobelas, 2005).

2.2.3.1. *Physiological adaptations of terrestrial biota to drought*

Isohydric plants stabilise their leaf water contents by adjusting stomatal opening as soil water potential decreases and atmospheric conditions dry, maintaining relatively constant leaf water content regardless of drought conditions. Mortality of these species by hydraulic failure per se may occur for seedlings or trees near their maximum height Future droughts are thought to kill isohydric species first via carbon starvation and subsequent predisposition to insect and pathogen attacks. Anisohydric species, by contrast, have a much slower stomatal reaction to drought stress and allow their leaf water content to decline as soil water content declines with drought. Mortality of these species will occur only if hydraulic failure is reached as a result of particularly intense droughts, prolonged drought duration, or in cases of edaphic (e.g. soil) or size (i.e. seedling and trees at maximum height) related constraints on hydraulic conductance. Although relatively drought-tolerant, anysohydric species are predisposed to hydraulic failure because they operate with narrower hydraulic safety margins during drought.

Many predisposing factors other than stomatal closure affect the severity of a drought's impact on animals and plants. Archaux and Wolters (2006) have summarised the different mechanism of drought resistance for terrestrial biodiversity, with emphasis on forest ecosystems. Examples for animals comprise thermo-regulation, moving to more protected areas and summer diapause. Production of antioxidant and compatible compounds, changes in cell membrane composition, rapid defoliation, morphological adaptation (e.g. deep-rooting) and seed bank have been listed for plants. A distinction is also made between factors that may vary between individuals of the same species, between phylogenetically related species (e.g taxa) or between ecosystems (but not between species within the same ecosystem). The short- to mid-term consequences of drought on biodiversity depend on species abilities to resist and to recover after drought as well as on competitive interactions between species, with the abundance of many species generally decreasing. Extreme drought events are thought to generate intense episodes of natural selection as some taxa may increase in number during drought or shortly after.

2.2.3.2. *Recovery from drought*

Recovery by biota varies markedly between seasonal and supra-seasonal droughts. Survival in refugia may strongly influence the capacity of the biota to recover from droughts once they break. Faunal recovery from seasonal droughts follows predictable sequences, whilst recovery from supra-seasonal droughts varies from one case to another and may be marked by dense populations of transient species and the depletion of biota that normally occur in the streams (Lake, 2005). Also the fauna of shallow wetlands normally subject to drying appear to have the capacity to survive in and recover from the impacts of severe drought (see Box 16). However, the capacity to persist may be compromised by either droughts of long duration or if the drought-resistant biota is depleted by false starts, filling events that do not persist long enough to allow reproduction (Lake, 2008).

Boulton (2003) has illustrated how postdrought recolonisation depends on the availability of refuges (related to physical habitat complexity, proximity to permanent water and macroinvertebrate life histories), the degree of habitat fragmentation and the changes wrought by low flows or drying (Figure below). Gjerlov et al. (2003) concluded that high refugium availability may reduce the effect of flow disturbance in streams in terms of macroinvertebrate mobility for recolonization.

Data from streams in the south-western U.S.A. suggest that recovery from drought by fish populations or assemblages in the region can be rapid. However, recent evidence suggests that extreme droughts do sometimes alter fish assemblages. Some of the knowledge gaps on the effects of drought on fish have recently been addressed, particularly additive effects of repeated drying episodes and whole-lake or basin-wide effects of drought, and in using molecular techniques to seek signals of drought at wide geographic scales because of events in the deep past. Hence species vulnerable to drought or water loss in streams may have disappeared from some basins in that region before the mid-1900s (Matthews and Marsh-Matthews, 2003).

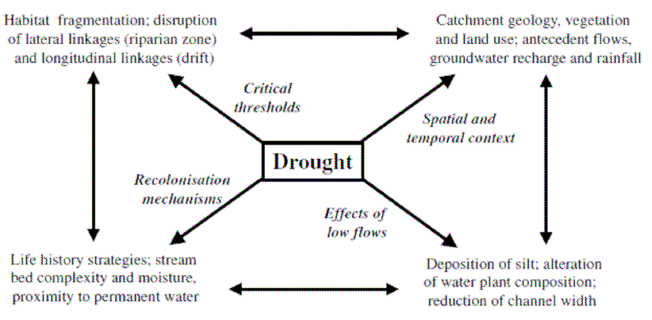

Figure: The relationship among low flows, critical thresholds, recolonisation mechanisms and the spatio-temporal context in the drought dynamics of aquatic macroinvertebrates. (Boulton, 2003)

Box 19 - Indicative examples of species recovery from drought from the latest studies

Resilient fishes from Australia's dryland rivers

To illustrate drought survival strategies, we can look at Australia's dryland rivers. These arid-zone rivers are acknowledged as being among the most variable and unpredictable in the world in terms of their flow regimes (Bunn et al., 2006). Many species in these river systems have traits that are conducive to survival during droughts and to population recovery after droughts. For example, they are widely distributed and often found in large numbers. They can recolonise and recruit in a wide array of habitat types only a few months after complete drying and extirpation of the previous fauna. They use a broad range of food types and have the capacity to move over large distances. They continue to produce offspring even in isolated waterholes and then take advantage of flooding for growth and recruitment.

The Lake Eyre golden perch or yellow belly (*Macquaria* sp.) appears to possess these traits. Species such as this can take advantage of the fundamental characteristics of the natural boom and bust hydro-ecological cycles, where they have not been modified by water abstraction or by dams and diversion of water to other catchments. In the Lerderberg River, Closs and Lake (1996) observed that, during drought, the relatively tolerant native fish species *Galaxius olidus* was able to survive in isolated pools, while the more finicky introduced species *Salmo trutta* was wiped out by the high temperatures.

Resilient macroinvertebrates from chalk streams in England and North American wetlands

Chalk streams are characterized by naturally regulated flow regimes whereas their headwaters, which are winterbourne streams, by periods of desiccation alternating with periods of high flow. Wood and Petts (1999) found that a severe summer rainfall deficit had no detectable deleterious impact on the macroinvertebrate community. This reflects the importance of winter groundwater recharge in sustaining summer flows in chalk streams. In contrast, they also found that an extended drought and periods of severe rainfall deficit in winters caused dramatic reductions in both river flow and the abundance of riverine macroinvertebrates. With the return of normal winter rainfall, recharge of the groundwater aquifer and river flow, however, the abundance of macroinvertebrates displayed a steady recovery. The recovery of chalk stream macroinvertebrate communities following severe low flows ultimately depends on the natural restoration of riverine habitats and the ability of the biota to recolonise parts of the stream from which they have been excluded. This is primarily dependant on the presence of refugia from which recolonisation can take place.

When studying the invertebrate assemblages of prairie wetlands in Minnesota, USA, Hershey et al. (1999) found that different invertebrate groups responded to severe drought in different ways. Gastropods and bivalves increased, whereas insects were less abundant and less diverse and took several years to recover. In the zooplankton, both rotifer and cladoceran abundance declined, but recovered fairly rapidly, whereas copepods and ostracods appeared to be unaffected by the drought. Wissinger and Gallagher (1999) compared temporary (autumnal) and permanent ponds and found that recovery from drought was much more strongly driven by the hatching of pre-drought fauna from drought-resistant stages in the autumnal ponds than in the permanent ponds, After a year, the autumnal pools had about 90% of the pre-drought fauna compared with about 77% for the permanent ponds.

2.3. Key challenges from a science perspective

- Freshwater ecosystems: Lake (2008) has gathered that the literature on the ecological effects of drought on freshwater ecosystems and their biota appears to be very scattered. This is because current knowledge of this topic has been generated from basically two types of sources: i) when drought intervenes with marked effects such as fish kills or algal blooms into a study not specifically directed at observing drought; ii) when a study follows the onset and the recovery from drought even though the focus was on drought. Many studies of drought being unplanned, they also are at small site scale. On the contrary, a full understanding of the nature and impacts of drought may be gained from taking a landscape approach at the spatial extent of a river basin. As a matter of fact, the extended effects of supraseasonal droughts are more severe, less predictable and more lasting in terms of lag effects. Studies on seasonal droughts are still more common than those of supra-season droughts of longer duration and less predictability (Lake, 2008).

- Aquatic flora: In terms of available data on responses to drought in flowing waters, Lake (2003) points out that more information is available on invertebrates and fish than on micro- and macroalgae, macrophytes and riparian plants. In a more recent study of McGowan et al. (2005), there were no marked differences in phytoplankton and zooplankton (copepods), but a major change in macrophyte assemblage structure occurred between the control and experimental drought lake. Whilst the pre-drought assemblage was dominated by *Ceratophyllum demersum*, after the drought it was by *Potamogeton pectinatus*. Thus, drought as a disturbance can create a new community state that may be stable. However, overall it is very evident from literature searches that there is a rather thin literature on the effects of drought on standing water bodies, especially lakes.

- Freshwater fish: Matthews and Marsj-Matthews (2003) have evaluated that gaps in knowledge exist on effects on fish of long-term droughts (decades to centuries), influence of drought on fish effects in ecosystems, and at the spatial scale of river basins to subcontinents. Gaps in knowledge also remain for effects of very short dry periods, on drought effects on higher levels of complexity, and on the manner in which droughts at the scale of decades affect fish. The authors also concluded that little is known about mechanisms by which droughts have direct or indirect effects on fish, the roles of droughts in the evolution of fish species, and the ways droughts alter effects of fish in ecosystems. Although global climate changes may have serious consequences for future local or regional fish faunas, ongoing studies of fish experiencing drought may aid in future conservation of what will become species at risk under climate-change scenarios. Advancing understanding of the potential responses to drought by fish or the relationships between fish and flow patterns will be instrumental to overcoming the difficulty of predicting ecological outcomes in response to a particular managed flow event or flow regime (King et al., 2010).

- Macroinvertebrates: There have been reviews of the effects of drought on freshwater biota (Humphries and Baldwin, 2003; Bond et al., 2008). However, few studies have addressed the influence of interactions between hydrology and channel morphology on the macroinvertebrate community using time-series data replicated across multiple locations and geographical regions (Dunbar et al., 2010). For example, Gilbert et al. (2008) found that abnormal communities of benthic macroinvertebrates occur after recurring episodes of drought in forested upland streams in south-central Ontario (Canada). Headwater ecosystems are thought to be ideally suited as early warning indicators of the potential impacts of future drought effects on aquatic biota. Hence the suggestion that further and sustained monitoring of headwater streams is needed in order to develop management strategies to address the impact of drought on ecosystems. Wood and Petts (1999) showed that there is also a need for the classification of droughts in relation to the impact on surface flows, groundwater levels and rainfall deficits. Droughts that have their origin in either the summer or winter may also have different impacts on both surface flows and the macroinvertebrate community. Any such classification system will need to consider the spatial and temporal components of individual droughts, both time of year and duration, and the potential threat of habitat and ecological degradation.

- Refuge habitats in aquatic ecosystems: Refuge size, disturbance intensity and mobility of organisms should play a large role in population persistence. Magoulick and Kobza (2003) have shown how the availability, the sizes and the spatial distribution of refugia during drought are influential not just on drought survival, but also on the nature and rate of subsequent recovery after the drought breaks. Whilst there is evidence to support the strong positive influence of refugia in surviving drought, Lake (2008) found that evidence to support the positive influence of refugia in patterns of drought recovery is fragmentary, with the exception of a few long-term studies of fish populations in wetlands of the Florida Everglades. Similarly, the identification of mechanisms and evolution of traits of freshwater biota to deal with drying and drought is incomplete at present. However, many findings of William's (2006) effective review of the biota of temporary waters are also applicable to drought. Magoulick and Kobza (2003) suggest that further research on the role of refuge use by fishes in response to drought is needed. Population dynamics of fishes using refugia during drought appear to be best modelled by modified source-sink dynamics, but dynamics are likely to change with spatial scale. Source-sink models have a source habitat that produces excess individuals that recolonise sink habitats. An understanding of refuge use and source-sink population dynamics is likely to enhance conservation of fishes subject to drought.

- Wetlands: In 2003 the Common Implementation Strategy working group B considered a number of issues to require further investigation such as i) defining more in detail how to include wetlands in the programme of measures for river basins, ii) recognizing the diversity of wetlands in the EU and therefore understanding the different ways in which wetlands restoration may contribute to river basin management, and iii) setting indicators for assessing the progress achieved regarding wetland restoration as part of river basin management plans. Following an expert workshop to identify knowledge gaps relating to wetland management under the EU Water Framework Directive, the European Wetlands Network recognized that many areas have not progressed as much as hoped for and proposed some priority research needs. Among these was i) improving wetland governance and management in terms of awareness-raising in the river basin community and protection through proper appreciation of ecosystem services such as drought avoidance and ii) identifying conceptual modelling that integrates different disciplines and moves towards a probabilistic/numerical form. For wetland hydro-geologists, conceptual models mean a description of the wetland in terms of its functional linkages i.e.– the extent to which it is supported by groundwater or surface water inputs, how this changes over time, and linkage to the different sources of pollution which might impact upon that wetland. For wetland ecologists, the conceptual model will focus on the zonation of the wetland, and the different species which are prevalent in each of them (Midgley, 2009).- Plant responses to drought stress are complex and determined by genetic and environmental factors. Optimisation of water use in the field requires an integrative systems approach that considers crop management, environmental and genetic factors. Parry, Flexas and Medrano (2005) suggest that research priorities focus on the prospects for crop and soil management and plant breeding and biotechnology that are needed to achieve high stable yield under drought. This research should combine the latest genomics resources including quantitative genetics, genomics and biomathematics with an ecophysiological understanding of the interactions between crop plant genotypes and the growing environment to better inform crop improvement. Isohydric and anisohydric regulation of leaf water potential may be an effective approach to modeling plant survival and mortality under future climate conditions (McDowell et al., 2008).

- Forestry and forest ecosystems: Archaux and Wolters' review (2006) has revealed that the impact of drought on ecosystem processes is a priority in future research because of the need to better understand how drought alters ecological functions and how these effects are influenced by species composition. In addition, these authors have pointed out that forestry research should focus on the simultaneous effects of drought and other factors, such as forest management, pollution and global warming. The effects of drought events on forest biodiversity should be considered in both planning (e.g. tree species selection) and management (e.g. retention of deadwood). Paoletti et al. (2007) report that emerging research needs on the interactive effects of air pollution and drought on forest ecosystems include understanding the impacts on soil fauna and phyllosphere biota as well as on plant phenology and reproductive fitness, and establishing trophic, competitive, and host/parasite relationship under changing pollution and climate regimes, including mycorrhizas and forest pests.

- Livestock: Drought is likely to affect livestock and cropping sectors differently. In areas where crops and animals occupy the same ecological zone, farming is likely to be a more risky business, herds being able to compensate for localised rainfall shortages by movement to better favoured areas (FAO, 1985).One of the aims of drought management policies is thus to understand the extent to which livestock mortality in arid lands influences cattle demography and is caused by population density or related to the pre-drought stocking rates as well as to increase offtake or help the pastoralists replace breeding females during recovery (Oba, 2001). The effect of other factors in combination with water availability should be further studied in non-tropic climates. Begzsuren et al. (2004) investigated how both droughts and severe winter weather control livestock mortality in a steppe ecosystem of the Gobi Desert in Mongolia. Livestock mortality appears to be more sensitive to severe winter weather than to droughts, and that the former contributes more to livestock mortality even years where combined drought and winter storms occur.

- Terrestrial fauna: Parmesan, Root and Willig (2000) have concluded that knowledge of precise causal factors of species' response to climate change is usually unavailable except for at least two groups of animals, the Lepidoptera (butterflies and moths) and birds. In both groups, extreme weather events such as drought appear to drive local population dynamics. The reason for this research gap is lack of either mechanistic understanding or sufficiently detailed observations during relevant periods of time. Coupling of more detailed climatological analyses to biological processes will help identify the impacts of specific facets of a complex climatic regime on natural systems. Specifically, changes in extreme drought events and in duration of time periods exceeding biological thresholds for temperature or precipitation are often neglected in CO_2 scenarios. Also, the two most commonly measured forms of biological response to climate change are changes in species' geographical distributions and in timing of activity.

- Impact thresholds: there are few models that summarise information about changes in water quality variables and consequences for ecosystems. In addition, methods are needed to relate changing river flows to ecological response, particularly those which do not require collection of extensive new data for river segments that lack historical data (Dunbar et al., 2010). Nonetheless, a number of approaches to river health assessment and indicator systems have been developed for key hydrologic, hydraulic and geomorphic features of streams (Ladson, 2003). Whether biological indicators react to extreme hydrological events in a timely enough manner for early warning systems and useful forecasts is yet to be assessed. Likewise, limited knowledge is available on how to improve the buffering capacity of ecosystems, especially in relation to headwaters, riparian areas, and connectivity, and what restoration measures would allow for preservation or enhancement of ecosystems resilience.

- Biodiversity: observation and modelling studies have shown that the major impacts of drought on biodiversity may include changes in seasonal timings, shifts in the distribution of species, changes in habitat composition and structure as species move northwards, including the expected increase in invasive species and diseases, and the impact of changing land use as agriculture, water, forestry and other countryside industries and interests react to water stress. A sectoral report on biodiversity of the European Climate Change Programme's Working Group on Impacts and Adaptation (2006) points out that a full overview of Member State activities is missing, as there is no consistent monitoring and reporting on biodiversity and related policy planning and implementation at the Members State level. Moreover, the most vulnerable biotopes and species are often either not known or not systematically monitored and thus cannot yet be addressed by dedicated adaptation measures. Gaps also exist in developing management practices for natural, semi-natural and human-use land areas such as agriculture to respond to the new movements and distributions of species and to what these community changes will imply. In order to reduce the impacts of future droughts on biodiversity, the resilience of the existing suite of sites and species should be built while also seeking to accommodate and facilitate the inevitable responses of biodiversity to climate change.

- Biodiversity conservation in river basins: A need has been recognized to shift from site prioritization to managing the whole ecosystem in a basin to reduce or allow transitions. Individual species are the building blocks of biological communities; habitats and ecosystems and thus conservation efforts must not lose the species focus, as biodiversity policies develop to encompass both protected areas and the wider countryside. However, focus only on one single species is not recommended. Environmental habitats change because of changes in water availability following extractions and/or climate change and habitat fragmentation restricts movement (Lake et al., 2000; Zaidman et al., 2002). Whilst protected areas have an important role to play as refugia, a landscape approach is considered to be most relevant because of the need to improve landscape-scale connectivity and permeability. Current management plans for protected areas do not allow for flexibility to adjust restoration and conservation measures to changing drought patterns. The new paradigm implies working with changing water availability while maintaining the integrity of ecosystems. Knowledge gaps in this area of research have been only partially addressed by a few initiatives (See box in section 2.1).

- Ecosystem management and water triage: there is a risk for certain ecosystems such as dense forests to be questioned for their water-efficiency in a drying climate. Decisions will thus need to be made about how much of the water deficit can be shared with ecosystems and how the water needs of ecosystems can be balanced with societal needs. As in medicine, water triage would acknowledge that some ecosystems need little intervention, some are sacrificeable to other land uses, and some are worth the intervention to restore (Craig, 2007). In this respect, tools will be needed to assess the willingness to pay for the various ecosystems and prioritize management responses to drought based on an impact hierarchy.

- Scale: Fish, invertebrate and plant populations and assemblages seem to recover rapidly from drought. Most studies of the effects of drought, however, have arisen fortuitously or have been commissioned after the impacts have already been felt. This is partly because it is difficult to distinguish between a prolonged drought due to climate variability and long-term decline in rainfall and streamflow as a result of climate change. Most research has also involved relatively short temporal, and small spatial, scales, focusing on specific ecological processes. Innovative approaches, such as microsatellite DNA analyses, can reveal that the effects of drought may be profound and long-lasting, resulting in population bottlenecks and altering the course of the evolution of species (Humphries and Baldwin, 2003). How much water a river ecosystem needs in drought requires understanding of the direct and indirect interactions between flows and biota over a range of time and space scales. It requires consideration of the flow variability over tens of years; it involves consideration of sector-scale habitat mosaics and micro-scale hydraulics (Petts, 2009). Assessing the long-term impacts of drought would help understand where and how much of the different ecosystems it may be appropriate to restore, i.e. whether hotspots such as protected areas or large-scale interventions on landscapes. The International Long Term Ecological Research (ILTER) network and the Ecological Limits of Hydrologic Alteration (ELOHA) framework for assessing and managing environmental flows across large regions are two exaples of the ongoing research efforts to address time and spatial knowledge gaps, respectively.

3. Impacts of droughts across different climatic conditions in Europe and worldwide

3.1. The different climate conditions in Europe

Climate and drought are closely connected. Indeed, the way drought develop in time and space depends is mainly governed by the meteorological processes. Drought results from lack of precipitation high temperature anomalies in the warm season and low temperature anomalies in the cold season during an extended period (for more details on the physical aspects, Tallaksen and Van Lanen, 2004). Expecting a common definition for drought is unrealistic since the underlying climatic processes are numerous. There is a great variety in the way to define climate. The most popular classification is the Köppen Climate Classification System (1936) based on the annual and monthly averages of temperature and precipitation. According to this classification, four main climate types are observed in Europe: cold D, arid B, temperate C and polar E.

Under temperate oceanic climate climate (dominant climate type in western Europe), different types of drought coexist. Examples are provided for France by Vidal et al. (2009) and for northwestern France by Planchon et al. (2008). Planchon at al. (2008) isolated years with major drought during the late XIXth and XXth century and classified them according to the occurrence within the year: Type 1 (spring and summer): 1896, 1921, 1949, 1976, and secondarily (shorter period of drought) 1900, 1911; Type 2 (summer drought): 1898, 1928, 1933, 1952, 1959, 1885 and 1887, 1919, Type 3 (winter drought): 1891, 1905, 1934, Type 4 (aseasonal): 1915, 1972. A list of major events was also produced at European scale within the ARIDE research project (Water Institute, 2000). Regarding regional annual precipitation, a large part of Europe experienced major droughts in 1904-1906, 1920-1921, 1932-1933, 1943-1944, 1948-1949, 1972-1973, 1975-1976 and 1988-1989. The recent 2003 drought provides an opportunity to examine the ecosystem tolerance to drought and question the drought mitigation strategies (354 scientific papers which analysed/discussed the effect of the 2003 drought have been published (search from Web of Science)).

Each event has its own specificities and its impact on the environment depends on the severity, the duration and the occurrence, i.e., whether it corresponds to the sensitive stage for the development of specific flora or fauna or to the peak of water demand for human uses. In addition, some regions are more vulnerable than others, both to expected physical changes and to the consequences they will have for ways of life. In particular, mountainous regions are recognized as particularly sensitive physical environments with populations whose histories and current social positions often strain local capacity to accommodate intense and rapid changes to their resource base.

In this context, the European Commission has recently funded a research project entitled ACQWA, Assessing Climate change and impacts on the Quantity and quality of WAter (www.acqwa.ch). The objectives of the ACQWA project are to assess the impacts of a changing climate on the hydrologic cycle in mountain regions, focusing on the quantity and quality of water. Special attention is paid to regions where snow- and ice melt represent a large contribution to streamflow. Another project is ADAPTALP. ADAPTation to climate change in the ALPine space (www.adaptalp.org) is an Alpine Space Programme (Priority 3: Environment and Risk Prevention) project, with 16 project partners aiming to assess impacts of and adaptation to climate change in the Alpine Space. Several aspects related to the impact of climate change in the Alps are investigated. One work package is dedicated to trend detection in the hydrological river flow regime of Alpine basins with a focus on trends on low flows. In addition, the project aims at modelling run-off and soil erosion to carry out impact studies and to suggest recommendations for adaptation measures and policies.

3.1.1. Vulnerability of species to drought across Europe

In broadest terms, latitudinal regions with similar climates will have similar types of lotic systems, but numerous variants correspond to local differences in underlying rocks, topography, plants, and animals (Resh et al., 1988).

The responses of biota are species-specific (low or high resistance and low or high resilience to these events). These responses are also dependant to the present climate and will evolve in parallel to the meteorological forcing. Some references on impact of droughts on ecosystem have been listed in the following table:

Climate	Area under study	Purpose	References
Humid continental climate	West Virginia (U.S.)	Effect on stream morphology and fish community	Hakala and Hartman, 2004
Humid oceanic climate	North-west England	Effect on fish community with a focus on refugia	Elliott, 2000
Humid oceanic climate	Kent (North-east England)	Impact on macroinvertebrate	Wood and Petts, 1999
Temperate continental climate	South-Central Ontario	Impact on macroinvertebrate	Gilbert et al., 2008
Temperate climate	Selwyn district (South Island, New Zealand)	Impact on fish community	Davey and Kelly, 2007
Temperate climate	Upper Mississippi River basin	Resilience of fish community after severe droughts	Adams, S.B., Warren, M.L.Jr, 2005
Mediterranean climate	Torgal basin (South-west Portugal)	Impact of supra-seasonal droughts on fish coimmunity	Magalhães et al., 2007

Table: Recent studies on the impact of droughts on ecosystem under different climates (*partial* list).

The studies help to understand the variability of the responses by replacing the changes in the abundance of species within the natural variability of climate through indices qualifying the occurrence of wet and dry periods. More severe and more frequent droughts are expected during the 20th century, in particular in the Mediterranean area. Drought is reported as a past threat for 41 species of Mediterranean endemic freshwater fish, a present threat for 112 species, and a future threat for 180 species (Smith and Darwall, 2006). The disappearance of breeding habitats due to drought is also enlisted as one of the biggest impact threatening the survival of Mediterranean dragonflies (Riservato et al., 2009). Research papers focus on observed abnormal droughts. Investigating severe droughts in the past, i.e. what could be normal drought conditions in the future provides knowledge on the expected response of biota. The findings of research projects may help to preserve the ecosystem as it is, under modified climate (EWD).

3.1.2. Water-dependent habitats of Europe

The Water Framework Directive takes account of areas which are protected under other EU Directives. Protected Areas for nature conservation include Special Areas of Conservation (SACs) as per the Habitats Directive, Special Protection Areas as per the Birds Directive, and (proposed) Natural Heritage Areas. The Habitats Directive lists the rare habitats which need protection in Annex 1, with the most vulnerable or unique as exclusively found within the European Union qualifying as “priority habitats”. Although all habitats, plants and animals need water, some particularly depend on it.

Priority Annex I-listed habitats can be groundwater-, precipitation- or surface water-dependant. Examples of groundwater-dependant habitats include turloughs, petrifying springs with tufa formation, and calcareous fens. Bogs are typicial precipitation-dependant habitats whereas alluvial forests are surface water-dependant habitats although there can be groundwater inputs as well. Turloughs, calcareous fens and bog woodland can have both surface water and ground water inputs. However, turloughs are depressions in karst which usually become inundated with groundwater during the winter and drain in summer through swallow holes connected to underground water systems. Mainly occurring in Ireland, these ecosystems typically contain distinctive aquatic and terrestrial plant and animal communities adapted to fluctuating water levels (Kilroy et al., 2005).

In the context of groundwater- depndendent ecosystems, the GENESIS project (www.thegenesisproject.eu) is aimed at defining a new scientific and technological basis for assessing climate change and land-use impacts on groundwater. The objective is to integrate pre-existing and new scientific knowledge into new methods, concepts and tools for the revision of the Ground Water Directive and better management of groundwater resources. 16 sites all over Europe are being studied in the GENESIS project to test project hypothesis, understand systems, and develop tools for monitoring and management. The developed results and tools will be tested at different sites to assess transferability of results in order to solve problems related to different type of groundwater systems at a European scale.

Non–priority Annex 1-listed water-dependent habitats range from i) sub-tidal, estuarine, shore, saltmarsh, and vegetated cliff habitats; ii) dystrophic, acid oligotrophic, hard water oligo-mesotrophic, and naturally eutrophic lakes; iii) some types of river plant communities; iv) some types of marsh, swamp, grassland, and bog habitats; to v) wet heath. Also coastal habitats are maintained by a number of coastal geomorphological processes. Lagoons, fixed dunes and machair usually depend on several water sources, be these coastal, transitional, surface or ground water to be maintained and, usually.

3.1.3. Mediterranean temporary ponds

Mediterranean temporary ponds are an indicative example of sensitive European habitat. According to Grillas et al. (2004) and Ruiz (2008), Mediterranean temporary ponds are small, very shallow water bodies, isolated from permanent water bodies, which undergo a periodic cycle of flooding and drought. The alternation of different environmental conditions between periods of submersion and periods of emersion promotes a characteristic flora and fauna that is adapted to a neither entirely aquatic nor terrestrial ecosystem. In terms of spatial distribution, the species that inhabit at the pond edges are generally endowed with more resistant traits to prolonged lack of water.

When under water, oxygen and carbon dioxide are hardly available to plants which have thereby developed suitable adaptations such as cuticle thinning, carbonate-based photosynthesis, etc. As the dry period sets in and water levels drop, lack of soil moisture becomes the limiting factor. Therefore, invertebrate or amphibian metamorphosis occurs earlier whereas small crustaceans have a very short life-cycle and resort to drought-resistant eggs. These are a typical component of the fauna, with some species living exclusively in these ponds. Also Mediterranean dragonflies display several adaptation mechanisms against summer drought ranging from diapause and regulation of the number of breeds per year, to migratory and re-colonisation behaviour

The flora is mainly composed of Mediterranean species that are also conditioned by a short life cycle and must produce seeds before the dry season, which favours the annual grass weeds. Mediterranean temporary ponds have a unique value due to their particular communities of plants, especially aquatic ferns (*Isoetes*). As such, theycan be concerned with the provisions of both the Habitat Directive and the Water Framework Directive. As an adaptation, *Isoetes* tend to be opportunistic and are capable of sudden rehydration. The seed bank and invertebrate cysts may resist long periods of desiccation, sometimes for years. However, a prolonged drought may lead to significant loss of diversity and, in extreme cases, to complete loss of functional habitat. It is therefore important in terms of management to control reductions in groundwater quantity/availability not to lead to desiccation of ponds that are mainly fed by groundwater and cause the eventual loss of habitat.

Climate change is likely to prolong inundation periods after intense rainfall as well as shorten these periods after prolonged droughts, or even prevent pond inundation during several years. In addition, construction of wells around temporary ponds and tree planting (especially Eucalyptus) aggravate aquifer depletion and impact negatively on the pond hydrology. Even the positive effect of eradicating invasive species of fish may be turned down by crayfish species that can survive the dry season by digging deep holes in the sediment (Ruiz, 2008).

3.2. Learning from past drought experiences

3.2.1. Impact of 2003 summer drought in France

The summer drought of 2003 observed in Europe was exceptional in terms of intensity, spatial extension and duration (two weeks between the 1rst to 15th August). This drought mainly affected Portugal, Spain, France and Italy. The effects on economy and environment are summarized in the Environment Alert Bulletin published by the United Nations Environment Programme.

Summer 2003 is believed to be the hottest in France for the past 50 years. Below normal rainfall was recorded for most of France from February until August 2002. In some areas the period from June to August 2002 saw a maximum temperature anomaly exceeding +4°C above the average. Water deficit reached 50% in Corsica and in the East Centre of France. Very high daytime temperatures (above 35°C) were recorded at two thirds of the stations of the French meteorological observation network. Days with temperature higher than 40°C were observed in 15 % of the cities. In France, the absolute temperature record for this event reached 44,1°C at St Christol-les-Alès and at Conqueyrac (Gard, South France), exceeding the previous record of 44°C observed at Toulouse-Francazal in summer 1923 (source: Meteo-France).

High temperatures and water deficit for most of France have weakened numerous ecosystems (e.g. soil water content, dry vegetation). During 2003 summer, observations on the forests of the Provence-Alpes-Côte d'Azur Region show that the three main conifers (Pinus pinaster, Pinus halepensis and Pinus silvestris) lost a strong proportion of their leaves (40-60 %) that induced a pluriannual decrease of their photosynthesis capacity. Since growth is affected by temperature, annual ring for 2003 is thin, demonstrating high stress conditions the previous spring. Broad-leaved trees lost their 2 and 3 earlier than usual. New shoots developed in autumn, but this abnormal growth exhausted the reserves, and at last most of these new shoots survive frost conditions in next winter. Impacts of this event were numerous on vegetation, and effects continued to be felt well four years later. This area experienced in addition drought conditions in spring 2004 to 2007 that reduce the resilience processes.

The exceptionally dry conditions resulted in forest fires in Europe. In France, the burned area in 2003 (73 000 ha) is the highest observed since 1991 is comparable to the ones observed during previous drought 1976, 1989 and 1990 (source: French ministry of agriculture).

The very high air temperature, solar radiation and low flow levels from the beginning of July to the beginning of September, caused high water temperature, and lead to critical condition for freshwater fishes. Indeed, water temperatures closed to or above 30°C were observed for most of the main French rivers. Travade and Carry (2004) have analysed the effect of the 2003 summer heat wave on four species of migratory diadromous fish (Atlantic salmon, shad, eel and sea lamprey). Two sites in South West France were examined: the first one is located along the Dordogne river; the second one located along the Garonne river downstream to a nuclear plant is impacted by thermal discharges. Results show that the prolonged drought modified seasonal behaviour of the species: seasonal migration was stopped between 2 and 4 weeks earlier than normal, when water temperatures reached 26°C for the eel and 23°C-24°C for the three other species. The results of the annual migration fish count showed declining salmon populations in the two river systems. This reduction could be explained by high temperature upstream to the estuary and high mortality downstream to the counting stations. Similarities observed at both sites suggest that the additional impact of the nuclear plant In terms of thermal pollution is minor.

3.2.2. Impacts of drought in cool temperate and boreal regions

Runoff in the Canadian prairies is over 80% derived from snowmelt. In glacially formed pothole depressions with no outlets, wetlands fill the depression in wet years and are underlain by a heavy glacial till that impedes groundwater exchange. Results showed that much lower precipitation and snow accumulation, shorter snow-covered duration, enhanced winter evaporation, and much lower discharge to the wetland from basin snowmelt runoff developed in the severe drought years 1999–2002. As a result, discharge to the wetland was 84% less on average than the wet period of 2005-2006 (Fang and Pomeroy, 2008).

The prairie pothole region in the heart of North America contains millions of these glacially formed, depressional wetlands embedded in a landscape matrix of natural grassland and agriculture, which provide valuable ecosystem services and produce 50% to 80% of the continent's ducks. Simulations suggest that the most productive habitat for breeding waterfowl would shift under a drier climate from the Dakotas and southeastern Saskatchewan to the wetter eastern and northern fringes, areas currently less productive or where most wetlands have been drained (Johnson et al., 2005). Water draining from peatlands of northern Europe also is likely to be sensitive to summer droughts in conjunction with permafrost thawing. As the melting shifts bogs and mires to fens and taiga forest, consequences are expected for GHG fluxes in these regions (IPCC, 2000).

3.2.3. Impacts of drought on coastal ecosystems of tropical regions

A study by Drexler and Ewel (2001) demonstrates how the impacts of shorter-term climate perturbations like the El Niño-Southern Oscillation on a Micronesian wetland complex can disrupt important coastal ecosystem processes. Over repeated drought cycles, such perturbations have the potential to affect the structure and function of mangrove forests and upstream ecosystems. Reduction in freshwater flows, associated drawdown in the water table and increased salinity near the surface are thought to reduce productivity in mangroves accustomed to flushing and nutrient/sediment inputs from freshwater flows. Drought-related impacts may also reduce recruitment and development of seedlings in both types of wetland. At the peak of the drought, the most dramatic result was a reversal in groundwater flow that sent groundwater from the mangroves upstream toward the adjacent freshwater swamp, thus illustrating the linkage between ecosystems. Over several drought cycles, reduced recruitment in both systems could lead to a number of changes in structure and functions, including an expansion landward of the mangroves and a concomitant shift upstream by the freshwater swamp.

Low-lying floodplains and associated swamps could be displaced by salt water habitats due to the combined actions of sea level rise, more intense monsoonal rains and droughts, and larger tidal/storm surges Other wetlands located in the continental interiors are more likely to be influenced by changes in the catchment hydrology. Whilst salt-tolerant species could expand from nearby coastal habitats, saltwater intrusion and inundation will eventually result in displacement of many wetland species (Bayliss et al., 1997). Both plants and animals species of coastal ecosystems are often valuable for local livelihoods, especially in tropical regions. Low-elevation coral atolls and smaller reef islands of the Pacific alike, the coastal wetlands in the Mediterranean and the Baltic have been identified as sensitive to the combined effect of accelerated sea level rise and other climate change impacts such as drought (Nicholls et al., 1999).

3.3. Key challenges from a science perspective

- to develop effective indicators and indices to detect and assess drought situations throughout Europe.

- to develop vulnerability assessment methodologies under different environmental conditions, including the predicted climate change in Europe

- to share experiences and to encourage database development (e.g. GIS platform and reliable database) at European level

- to facilitate expertise and experience feedback

- to support continuous observations (at least, one record per year) to make adaptation strategies for land and water management easier, since it is still difficult to asses future trends; in addition, past observations may not be sufficient: new conditions may emerge from climate change (we may expect more severe crises as responses to critical events that have never been experienced by the ecosystems); water temperature measurement requires more attention;

- to fill gaps in observations (have all the anthropogenic pressures been well documented? have all the hydraulic (dis)connections been identified? are river flows well predicted at ungauged sites?).

4. Strategies for reducing ecological and related socio-economic vulnerabilities to drought

The previous chapters have described how the impacts of drought on ecosystems can lead to water quality deterioration. This is the result of different abiotic and biotic factors, including increased pollution of receiving water bodies due to the lower amount of water to dilute pollutant discharges, saline water intrusion in groundwater, blooms of toxic cyanobacteria following oxygen depletion, nutrients concentration and thermal pollution. Drought impacts on rivers, reservoirs and aquifers have been also addressed in terms of water supply problems. Low flows affect intakes of urban, industrial and agricultural systems. Drops in groundwater levels are in turn caused by increasing abstraction for existing water supply sources. Reductions in water storage capacity limit system flexibility to inter-basin transfers.

In a report on extreme hydrological events hindering sustainable water use in Europe, the EEA (2001) concludes that the main economic impacts of past drought events in European countries have been in terms of reductions in national electricity production, also due to lack of cooling water and distribution failures to the grid, increase in electricity consumption for pumping stations, and crop-damaging interaction with deep frost during dry winters. The economic costs associated with loss of crops and livestock often translates into reductions in crop and forage yield, unplanned slaughtering and reduction in milk production.

This chapter will explain the linkages between the ecological impacts of drought and related socio-economic vulnerabilities, such as those related to water use restrictions, supply cuts and water re-allocations, as well as present the key policy challenges for drought planning in the context of sustainable land and water management. These mainly relate with natural catchments as additional sources of water supply. Other policy responses to drought such as demand management and early warning systems have been addressed by the background documents on the socio-economic impacts of drought and drought management, respectively.

4.1. Ecosystem services and human well-being

Ecosystem services refer to the benefits society receives from ecosystems, direct or indirect (Acreman and Dunbar, 2004, Cork and Shelton, 2000; Daily, 1997). The challenge of climate change will result in a stronger focus on water allocations and the development of improved policy in these areas, especially as biodiversity conservation, household supply, industry, forestry, navigation and energy as sectors will feel the brunt of climate variability (EEA, 2009). Each of these sectors relies in different ways on the provision of ecosystem services, and therefore on the allocation principles and management strategies of and between sectors (e.g.: between forestry and energy). Many of these impacts on multiple sectors will require tough policy choices, as competition between sectors forces policy conflicts, e.g.: energy production from the growth of biofuels that require additional fertiliser application, land area and water supply, and policies to restore freshwaters from the effects of eutrophication and drought, or removal of forest biomass for bioenergy production may counter attempts to maintain surface water alkalinity (Batterbee et al., 2008).

Environment allocations of water are intended to maintain biodiversity, but also the provisioning services upon which society functions at a productive and livelihood level (Postel and Richter, 2002). Use of water through highly managed systems, such as those typical across Europe including reservoirs and dams, canals and embankments, and intensive irrigation often has a negative effect on the natural hydrological cycle (Forslund et al., 2009). Human use of products from forests, wetlands, oceans etc, and the functions the ecosystem performs in providing clean water, storing water, watering crops through rainfall, and providing climate services are the backbone to living standards across Europe. Ecosystems play a significant role in determining quantity and quality of water resources (Schröter et al., 2005). Furthermore, human well-being is reliant on these ecosystem services to produce water, food, and fibre for life.

The Millennium Ecosystem Assessment (2005) defined the link between human well-being and ecosystem services in terms of security, basic material for a good life, health and good social relations. However, these are difficult constituents to characterize across areas with ranges in living standards and different cultural requirements and expectations. From a livelihoods perspective natural capital (land, soil, water, forests and fisheries) are all ecosystem services, and all are reliant on water as the connecting element. In turn, healthy ecosystems provide physical, social, financial, and human capital to society, but the assets provided are all vulnerable to shocks such as drought (Chambers and Conway, 1992). Poorer communities are often less able to cope with shocks as they often rely most on primary services provided by ecosystems (Mainka et al., 2005; Silvius et al., 2000).

A critical element of understanding ecosystems services and the role they play in providing society with services is determining how, when and where the different services are provided and for how long (Hirji and Davis, 2009). The flow regime in rivers and streams is often the most critical element and refers to the magnitude, frequency and duration of water discharge (Poff et al., 1997), yet the changing climate poses grave threats to biodiversity, possibly threatening catastrophic loss of species in some regions of the world (Thomas et al., 2004). It is clear, therefore, that finding ways to reduce these threats needs to be a high-priority for adaptation strategies, including drought. The International Long Term Ecological Research (ILTER) network strives to understand what the interactions are among ecosystem services, ecosystem dynamics, and human outcomes and behavior. For example, it is commited to study to what extent cultural differences in the perception and use of ecosystem services constrain the resilience of social-ecological systems (Haberl et al., 2006).

Box 20 - Indicative example of freshwater ecosystem services

Wetlands for flood mitigation: the Lafnitz River, Austria (European Commission, 2003)

The Lafnitz is one of the few remaining natural lowland rivers in Austria. Since the mid 1980s about 220 ha of agricultural land have been purchased and managed more extensively. Another 610 ha have been taken out of intensive agricultural production through compensation payments to landowners. The area is used for natural flood storage. The original plan was to build dams along the river, but this would have caused a higher flood risk for the villages further downstream and it would have been more expensive. Extensive agricultural management on land surfaces prone to flooding is part of risk avoidance strategies practiced by floodplain peoples since ancient times. Such "soft" solutions are being revived by integrating high quality agricultural products grown under an extensive fashion with integrated river basin management and hold the promise of contributing to a more sustainable future cultural landscape.

The UN/ECE Guidelines on Sustainable Flood Prevention (2000) presented at the Water Directors meeting in Athens, June 2003, provides numerous best practices on flood prevention, protection and mitigation. Non-structural measures such as the storage effect of vegetation, soil, ground and wetlands are vital to mitigate effects of medium scale floods and beneficial in reducing sediment yield. The conservation, protection and restoration of degraded wetlands and floodplains, including river meanders, oxbows, and especially reconnecting rivers with their floodplains is a main preventive non-structural measure. Consideration of how wetlands can be used to manage floods and droughts in a manner compatible with WFD objectives could greatly assist Member States with implementation, and in integrating flood management strategies with RBMPs.

This list of potentially significant pressures on water ecosystems includes traditional 'hard' engineering solutions to flooding and drought problems (such as the canalisation of rivers, and the construction of walls, culverts and reservoirs), which may have significant impacts on the hydro-morphology of water bodies. They may also prove unsustainable in the long-term on the scale necessary to support people, property and the environment in the context of increased population growth and accelerating climate change. The role which wetland creation can play in offering alternatives to such 'hard' solutions is increasingly recognized.

Drought needs to be considered within wider water management strategies and approaches to maintain the integrity of freshwater systems. However, just as important to focus on the role of the environment is providing solutions to climate change adaptation, not just the threats that the environment faces. There are links to resilience that give the environment a critical role in climate change adaptation (Smith and Barchiesi, 2009). Sadoff and Grey (2002) argue that in order to accrue benefits 'from a river' (such as energy and food production, flood and drought management, navigation, recreation, good water quality) requires society to provide benefits 'to the river' through maintaining healthy and sustainable river basins which incorporate management strategies for drought periods.

Historic hydrology may no longer be a viable guide to the future management of river basins (Palmer et al., 2008). Environment has a critical role to play. Well-functioning watersheds and intact floodplains and coasts provide water storage, flood control and ultimately coastal defence. The environment itself is infrastructure for adaptation; it is 'natural infrastructure'. Hewes (2008) considers wetlands as a vital part of the United States water infrastructure. They provide untold benefits, from controlling floods and buffering communities from droughts to filtering pollutants and improving water quality.

Green infrastructure thinking may be an important tool in tackling climate variability such as droughts, through providing more natural cost-effective water storage options, and natural 'capture' of rainfall in urban areas and domestic re-use of water for green spaces (Beatley, 2000). When based on principles of good governance, sound investment strategies and learning from integrated water resources management, integrating natural infrastructure into adaptation helps build resilience (Nelson et al., 2007; EEA, 2010).

4.2. Drought management in the context of sustainable land and water management

This section has the purpose to present those topics with high priority in policy making that are also relevant for securing ecological conditions during drought. For a more comprehensive list of policy and management options, please refer to Deliverable 2.2 and 5.1 of this Project.

4.2.1. Eco-hydrology and ecological engineering

Eco-hydrology has been defined as 'the study of the functional interrelations between hydrology and biota at catchment scale', and even 'a new approach to achieve sustainable management of water' (Zalewski et al., 1997). Ecohydrology is a new integrative science that involves finding solutions to issues surrounding water, people, and the environment. One of the fundamental concepts involved in ecohydrology is that the timing and availability of freshwater is intimately linked to ecosystem processes, and the goods and services provided by freshwater to societies

According to Naiman et al. (2007) there are two contrasting definitions of eco-hydrology, depending on the approach from either an aquatic or terrestrial perspective. From an aquatic viewpoint, ecohydrology considers the relationships between hydrology and aquatic ecosystem processes and their biota, such as using ecosystem processes as tools to meet freshwater management goals (Zalewski, 2000). This effectively relies on the use of hydrological processes and ecological processes to enhance the overall integrity of aquatic ecosystems (eg. Zalewski, 2006), allowing humans to capitalize on the sustainability of ecosystem services. As Wagner and Zalewski (2000) demonstrated that ecohydrological approaches can be used to control pollution in lakes and reservoirs through manipulating water regimes, ecohydrology does have the potential to become broader and more effective through incorporating social and cultural considerations in the process (Hiwasaki and Arico, 2007).

Box 21 - Indicative example of ecohydrology application

Urban water management

Conventionally, urban water management has focused mainly on protecting the urban human population against hydrological extremes such as droughts and providing water services including water supply, drainage, and wastewater management. Sustainable urban draining systems have also emerged as a new approach to controlling stormwater pollution and protecting developing watersheds and already urbanized communities. Instead of large investments in complex and costly engineering strategies for stormwater management, these strategies integrate green space, native landscaping, natural hydrologic functions, and various other techniques to generate less runoff from developed land.

Terrestrial ecohydrology focuses more on ecological processes involved within the hydrological cycle, such as the soil profile as a growing medium and water reservoir eg. as green water (Falkenmark and Folke, 2002), and plant canopy level. Consequently, the emphasis is on evapo-transpiration, canopy interception, and thermodynamic balance at the land surface (Rodríguez-Iturbe, 2000; Rodríguez-Iturbe and Porporato, 2005). As a science this has remained more in academic circles and as yet has not been integrated into more operational water management approaches. With the development of drought management plans and the need for more information on the advance of drought and options to reduce vulnerability it may provide important findings in the future for understanding drought development and onset.

Ecohydrology is a science gaining recognition in the multidisciplinary areas between natural processes and engineering solutions to reduce environmental impact and to better understand ecological responses (Hannah et al., 2004). The interaction between the hydrological cycle and ecosystems is most intense when water is intermittently present. The fluctuating nature of the hydrological cycle, together with the network of dynamic links with the soil-climate-vegetation system complicates the processes involved (Rodriguez-Iturbe and Porporato, 2002). Soil moisture is the key variable which modulates the actions of climate, soil and vegetation on the soil profile water balance and the impact on vegetation (Laio et al., 2001). Soil acts as a regulator controlling evapotranspiration, runoff, and water redistribution (Noy-Meir, 1973). Rodriguez-Iturbe and Porporato (2002) identified scale as a key element to understanding soil and ecosystem interactions. Spatial and temporal scales dictate plant stress based on rainfall patterns and soil characteristics. Soil and nutrient cycles and the evolution of soil properties are interrelated with vegetation cycles. This is an area of science little studied by the disciplines involved (ecology and hydrology).

At continental scales, large scale patterns of vegetation types, water stress, and growth rates influence the dynamics and formation of precipitation. This connects ecohydrology to other new science areas such as hydrometeorology, as the feedback cycles become more complex and better understood. Witte et al. (2004) state that any research which implies empirical relationships between vegetation and habitat may rapidly lose their validity in a world where climate changes more rapidly and where return periods of extremes, such as drought, become more regular and prolonged. Modelling of ecosystem succession and feedbacks may therefore be too complex for us to understand at present.

At the continental scale seasonal transpiration and precipitation may have dramatic consequences on contributing to and coping with drought. Mediterranean climates experience concentrated rainfall in the winter season, the period of low evapotranspiration. This results in high soil water availability (supply) when evaporative and transpiration demand is lowest. At large scales, beyond field and farm levels the storage of this soil moisture for summer use and as a buffer to water shortages is under researched.

Ecohydrology does not specify the method of incorporating ecosystem processes into management programs, as that is site-specific. As part of the strategy, it focuses on understanding useful ecosystem processes and communicating that understanding to water managers in a way that enables incorporation into planned and existing programmes (Naiman et al., 2007). For example, groundwater recharge and groundwater discharge are important wetland functions for mitigating the effects of droughts that are also relevant to delivering the objectives of the WFD. In achieving good status, measures will have to be implemented to avoid or remedy any significant damage to directly dependent water bodies resulting from anthropogenic alterations (European Commission, 2003).

4.2.2. Ecosystem-based water management

Human actions can cause loss of resilience through removal of functional groups of species such as apex predators or benthic feeders, bottom-up impacts via polluting emissions or excess nutrient influx, or the alteration of the magnitude, frequency, and duration of disturbance regimes. Climate-led modifications of the hydrological cycle, hydropower operations, and water withdrawals for irrigation are all examples of such disturbances to the natural flow regime. The combination of the different categories of impacts erodes the self-repairing capacity of ecosystems until they cease to cope with ordinary change such as climate variability (Folke et al., 2004). Most importantly, the effects of climate change are exacerbated by each of these impacts that limit water quality and quantity. In the conditions of declining resilience, progressively smaller external events such as water withdrawals can cause irreversible shifts in flow regimes.

The Ecosystem Approach is a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way. It places human needs at the centre of biodiversity management. It aims to manage the ecosystem, based on the multiple functions that ecosystems perform and the multiple uses that are made of these functions. The ecosystem approach does not aim for short-term economic gains, but aims to optimize the use of an ecosystem without damaging it (Gill, 2004). According to the Eurolimpacs Project (2009), the management of ecosystems under drought conditions can be summarised as a 3-step process. Firstly, there is a need to identify key indicators of ecosystem health that clearly indicate impending or realized drought. Secondly, methods should be applied for defining reference conditions and restoration strategies for ecosystems in the context of drought. Thirdly, a decision support system should be provided to respond to the interactions between climate and other changes.

4.2.2.1. Drought indicators and restoration strategies

Organisms showing distinctive reactions to change are potentially useable as indicators of such change. Of particular interest are species that reflect the deterioration of ecosystems caused by climate change and those that are indicative of the recovery of ecosystems and provide tools for the development of restoration strategies. Ecological assessment and the use of indicator taxa are current foci of European freshwater research. However, existing indicator systems are designed primarily to monitor the effects of land-use and pollution; none is specifically designed to address climate change. Developing such a system is a key aim of the Euro-limpacs Project.

The first step in defining reference conditions and restoration strategies for ecosystems in the context of drought would be to identify and map refugia. Ideally, refugia show the following characteristics (Bond, 2007):

- Moisture or water is retained in the refuge throughout the drought.
- It is large enough to give the biota room to move, e.g. a large pool for large fish or turtles; a hole in the bank or pore space in the sediment beneath riverbed cobbles or snags for macroinvertebrates, or perhaps frogs or mussels.
- There is an adequate food supply for the period between rains for particular biota.
- The water quality and temperature remain within tolerable ranges for particular biota right through the drought.
- Intrusion by livestock or humans is minimal.

European Commission (2007) state that a clear prioritisation of water uses needs to be developed, especially during prolonged droughts where temporary failure to reach Good Ecological Status (GES) may occur. Environmental impacts are an important element in understanding the failure of reaching GES, as increased water temperatures during drought events are likely to affect chemical reaction kinetics, and when combined with deteriorations in water quality, freshwater ecological status (Whitehead et al., 2009). Suggestions by the European Commission (2007) for drought impact indicators include:

- Mortality of fish species
- Impacts on river banks and biodiversity (flora)
- Loss of biodiversity in terrestrial areas (depending on the aquatic system)
- Impact on wetlands
- Forest fire risk, and
- Ecological status

Restoration will change in approach depending on the drought. For example, droughts occurring at critical reproduction or migration periods for fish could have far greater impacts on species than during non-critical periods. This will require the development of qualitative indictors and not just simple fish death quantative indicators. Furthermore, the recovery of species and habitat from drought needs to be taken into account as part of restorative approaches. Rainfall following drought may not improve ecological status immediately, therefore returning wastewater discharge or industrial waste discharge to pre-drought allowances may cause a further reduction in GES. Progressive discharge allowances may be required to allow water habitats to recover before pre-drought levels are returned to, and should be considered in Drought Management Plans.

4.2.2.2. Introducing environmental flows

Where freshwater ecosystems are stressed, even at the onset of drought there could be complete collapse of valued aquatic ecosystems and the plant and animal species that comprise them. This is likely to occur unless rivers are allowed some flow during drought, or unless particular water levels or volumes are somehow maintained in standing water bodies. The recognition of the escalating hydrological alteration of rivers on a global scale and resultant environmental degradation has led to the establishment of the science of environmental flow assessment.

According to the 2007 Brisbane Declaration '*Environmental Flows describes the quantity, quality and timing of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems'*. Despite the strong conceptual basis for sustainable river management, scientists have been challenged to define ecosystem needs clearly enough to guide policy formulation and management actions that balance competing demands and goals. Environmental flows assessments can serve as a decision-support tool that mainstreams both ecosystems needs and climate change scenarios into water resources management, but measuring low flow streamflow even within 'normal' hydrological ranges, and quantifying the flow uncertainties is a challenge (e.g. Rees, et al., 2004; WMO, 2008). The majority of hydrological models have restricted potential in simulating low streamflow, and therefore the impact on highly dynamic ecosystems such as streams (Stanley et al., 1997). These uncertainties combine with uncertainty introduced by downscaling methods and bias correction (Wilby et al., 2006; Wilby and Harris, 2006; New et al., 2007; Prudhomme and Davies, 2009).

A global review of the present status of environmental flow methodologies by Tharme (2003) revealed the existence of some 207 individual methodologies used in more than 40 countries for contributing to the definition of a flow regime required for ecosystem conservation that could be differentiated into hydrological, hydraulic rating, habitat simulation and holistic methodologies, among others.

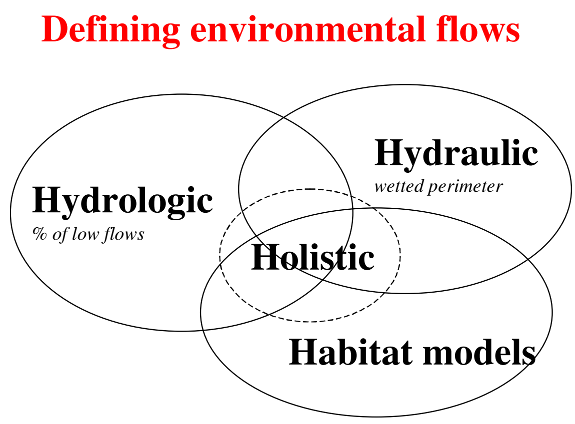

Figure: Scheme of definition for environmental flow

Hydrological methods define environmental flows as a percentage of a given flow statistic(s) (e.g. the mean annual flow, the mean monthly flow or various low flow statistics in other cases (Pyrce, 2004)). They influenced in the beginning national or regional legislation on minimum flows.

Habitat simulation methods aim at predicting how microhabitat conditions (depth, velocity and particle size and other characteristics) expressed in terms of habitat values vary regarding discharge. They are based on a hydraulic model of a stream reach combined with models of the habitat preferences of species or specific life stages. The time and the expertise (Lamouroux et al., 1999) can make the application of such models tricky when multi-dimensional hydraulic models are used (instead of 1D hydrodynamic models) or when estimates in multiple stream reaches are needed (e.g. for catchment-wide management).

Hydraulic methods have received less attention over time with the development of habitat simulation models (Lamouroux, 2008). The main assumption is that hydraulic parameters such as water depth or wetted perimeter are more likely reflecting important habitat features of aquatic organisms than hydrological characteristics alone. To be applied, these methods required limited number of cross-sections at different discharges. The simplicity of use allow generalized application and connections to GIS platforms to derive maps.

Holistic methods aim at addressing all aspects of the system functioning in an integrated approach. Thus, a high degree of expertise is needed for distinguishing the key processes involved with flow management.

In developed countries of the northern hemisphere, methods with emphasis on complex, hydrodynamic habitat modeling are most widely used (see http://www.eamn.org/ for a review of existing models). In developing world regions where environmental flow research is in its infancy and water allocations for ecosystems are based on best professional judgment, holistic methodologies may be especially appropriate. Centred in Australia and South Africa, these include considerations of ecosystem-dependent livelihoods and a benchmarking process suitable for evaluating alternative water resource developments at basin scale, in relatively poorly known systems. Existing and planned water projects represent thus opportunities to conduct ecosystem-scale experiments through controlled river flow manipulations (Poff et al., 2003).

According to Shafroth et al. (2010) improving knowledge and predictions of ecological responses to environmental flows comes down to two general approaches: i) coupling physical system models to ecological responses in the context of drought as Chapter 2 described in the context of drought; and ii) clarifying these empirical relationships between flow and ecological responses through implementation and monitoring of experimental flow releases as articulated in this section.

Until recently the equivalent water uses in, upstream of, and downstream of, a wetland have not always been given sufficient attention, and rather have been considered an external driving force more or less beyond the control of wetland managers. To improve water management the development of wetlands must be undertaken within the context of their larger surrounding "waterscape" as well their larger surrounding landscape. The aim should be to match water resources strategies with land use strategies, so that these can be implemented jointly to support the maintenance of healthy, functional wetlands that provide a full range of benefits/services for people (including water supply). Yet land use management and water management are generally the responsibilities of different agencies or authorities, resulting in a lack of alignment of objectives or priorities, which in turn leads to one or other of the land or water aspects of wetlands not being adequately protected or managed. Although there appears to be a general sequence of planning and management activities that can promote effective integration of wetlands into river basin management, the exact sequence is different for different countries, but what remains important is the fact that there is a formal, organized and transparent process established, with which all relevant sectors can engage. Developed by Dickens et al., (2004), the 'Critical Path' approach to integrating wetlands into river basin management evolved out of many experiences of the bottlenecks and obstacles to implementation of the protection, management and wise use of individual wetlands at site level in South Africa. Additional experience from implementation of environmental flows concepts and policies has also brought the recognition that there is a certain degree of sequencing required, between planning and management activities at river basin level and between management and user activities at individual wetland or site level. Activities need to be progressively initiated and completed, in time and through scales from basin scale down to site scale, in order to ensure the successful management and wise use of wetlands.

4.2.2.3. Building drought into river operational plans

For freshwater ecosystems, river operational plans already exist which take into account the balance of water allocation for extraction (such as for urban use or irrigation) and water for the environment, and the rules for managing this balance. During drought, water managers often find themselves adjusting the rules and changing the balance, to support human activities. Since the intensity, duration and geographical extent of drought cannot be predicted with reasonable accuracy, the challenge is for water managers to decide whether, when and where in the catchment to provide environmental flows to relieve stress in the river ecology.

Despite considerable progress in understanding how flow variability sustains river ecosystems, there is a growing temptation to ignore natural system complexity in favor of simplistic, static, environmental flow ''rules'' to resolve the pressing river management issues. In the absence of detailed empirical information of environmental flow requirements for rivers, a generic approach could be used to avoid misguided adaptation. This approach incorporate essential aspects of natural flow variability shared across particular classes of rivers that can be validated with empirical biological data and other information in a calibration process (Arthington et al., 2006).

Bunn and Arthington (2002) have grouped the essential aspects of natural flow variability in four key principles that highlight the ecological consequences of altered flow regimes for aquatic biodiversity (Figure below). Firstly, flow is a major determinant of physical habitat in streams, which in turn is a major determinant of biotic composition. Secondly, aquatic species have evolved life history strategies primarily in direct response to the natural flow regimes, including droughts. Thirdly, maintenance of natural patterns of longitudinal and lateral connectivity is essential to the viability of populations of many riverine species. Increasingly occurring droughts are a threat to this connectivity. Finally, the invasion and success of exotic and introduced species in rivers is facilitated by the alteration of flow regimes such as during prolonged low flows. River operational plans should consider all these principles when addressing the impacts of droughts on aquatic biodiversity.

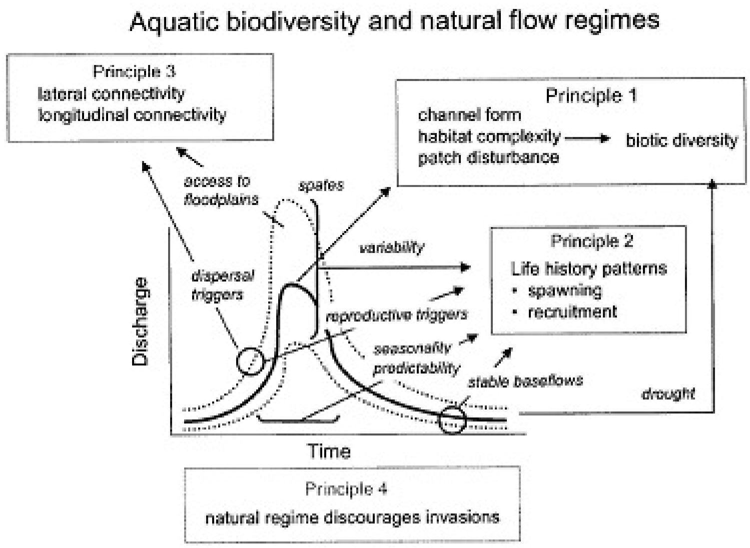

Figure: The four principles of how the flow regime is the key driver of river and floodplain ecosystems (Bunn and Arthington, 2002)

In many basins, flows regimes are still classified by only following simple hydrological criteria (such as a percentage of annual flow) without considering the requirements of ecosystems in relation to temporal distribution and water quality. Operational water management has historically assumed a level of annual or decadal climate "stationarity", based on historic records of seasonal variation as a good indication of future hydrology (Matthews and Le Quesne, 2009). Yet many regulated river systems show a decline in environmental condition due to an increase in hydrological stability (e.g.: Gallardo et al., 2008; Lake et al., 2007; Franklin et al., 2008; and Growns, 2007). River engineers and planners focus on managing rivers based on these assumptions, although there is often little planning for low flows in rivers, or the wider effects and needs of changing flow regimes on lakes, groundwater, and estuaries (Young, 2004).

Any reduction in the status of water bodies (which can be temporary under the WFD [Article 4, para.6]) may call for a relaxation to be applied to environmental constraints, although further degradation in the status of water bodies needs to be counterbalanced by looking at options such as alternate means for achieving water quality through water treament to preserve quality, and through augmentation of surface waters supplied from groundwater. Ideally, any reduction in minimum flows required to preseve waterbody ecological status should have been previously analysed to determine the negative effects of these changes on the ecological status (including aquatic fauna and flora). It should be noted that during extreme and/or prolonged droughts changes to flow regimes may have irrieversible effects on aquatic fauna and flora and other surrounding habitat (e.g. shelterbelts, riparian vegetation) (MED Joint Process WFD/EUWI, 2006). Any alterations to allocation patterns should ideally be made in a transparent and comprehensive manner on a regular basis to raise awareness abojut the status of water reosurces, water reserves, and the possible impact on the environment (Videira et al., 2006).

4.2.3. Integration with Water Resources Management (IWRM)

GWP/INBO (2009) defines integrated water resources management as an approach that "helps to manage and develop water resources in a sustainable and balanced way, taking account of social, economic and environmental interests. It recognises the many different and competing interest groups, the sectors that use and abuse water, and the needs of the environment. The integrated approach co-ordinates water resources management across sectors and interest groups, and at different scales, from local to international. It emphasises involvement in national policy and law making processes, establishing good governance and creating effective institutional and regulatory arrangements as routes to more equitable and sustainable decisions. A range of tools, such as social and environmental assessments, economic instruments, and information and monitoring systems, support this process."

Catchments, basins and groundwater recharge areas are the natural units for IWRM. This is to understand and balance competing water uses and to mobilize meaningful stakeholder and public participation across administrative and human defined boundaries- This is especially important as droughts are transboundary and multi-catchment in geographic range. Considering that the hundreds of large transboundary river basins and aquifers around the world often consist of a unique ecosystem shared among several political areas, IWRM can be a good example of how to apply the Ecosystem Approach as well as an enabling framework for planning and implementing development in all sectors through an IWRM approach. This level of integration is not new to the rolling global debate on IWRM (e.g.: Savenije and Van der Zaag, 2008; Sadoff and Muller, 2009, etc), and should form a logical part of integrating links between IWRM and National Action Planning (e.g.; to disasters and adaptation to climate change). This will require further and better inter-disciplinary working for research to operational management and policy level. Within the Water Framework Directive there are two classification systems: (i) ecological status which uses biological and physico-chemical parameters, and; (ii) a chemical classification, which is an assessment of compliance with priority hazardous substances. Deviation for reference conditions in waterbodies is primarily measured through (i) fish; (ii) invertebrates, and (iii) macrophytes and algae. These parameters determine the ecological status of the waterbody, with all EU Member States in agreement to achieve 'good ecological status' and to prevent further degradation.

The role of environmental flows is not explicit in the WFD. The WFD is concerned with protection and restoration of rivers, but hydrological modification is not used to assess the ecological status of the river. Therefore, alterations in flow regime (i.e.: increasing extraction) will not affect the status of the river unless the actual biology is affected (Acreman, 2009; 2007). This may result in additional abstraction from rivers, i.e.: for irrigation in the face of rising temperatures due to climate variability. Provided there is no change to ecological status of the river this may not be seen as a concern for water managers. However, during drought conditions the cumulative extraction from the river or waterbody may cause rapid or long-lasting detrimental ecological damage.

Furthermore, restoring more natural flow patterns through applying environmental flows may improve the ecological status of some rivers, and recovery needs to be considered in basin where allocations already exceed water availability, leaving no water for environmental flows, especially during drought periods. This is important as often the environment is not viewed or understood as a water user, although in reality it is a major consumer and provider. Infrastructure development affects ecosystems, both upstream and downstream, and therefore the communities and services which rely on those ecosystems. Taking an IWRM approaches legitimises the role of environment as a water user (through the Dublin Principles), therefore environmental flow requirements to support downstream water use and ecosystem services should be integral parts of both strategic policy and consequential planning (through the Programme of Measures [WFD Article 11, 13]), but also at the tactical level through projects and programmes implemented and regulated by governments.

4.3. Learning from Australia's experience with drought management and policy

Australia, a country which suffers from recurrent droughts, is currently experiencing a shift in climate. It is often classified as the driest inhabited continent due to the extremely low annual average rainfall (465 mm) and associated low annual average runoff (57 mm). This has required a regular revision of Australia's water policy to align with the needs of its society. Several changes in water policy have been formulated in recent times with the objective of striking a balance between the consumptive and environmental components of flows in Australian catchments. Some of the developments that affect irrigated agriculture include: (i) the Council of Australian Government's water reforms; (ii) the Murray–Darling Basin Commission cap (the volume of water that could be diverted under 1993–94 levels of development); (iii) environmental flow rules; and (iv) the National Water Initiative.

At a strategic level global climate change threatens the viability of irrigated agriculture and other industries. Under the present water reforms, longer-term water security is not guaranteed because these reforms do not explicitly take into account threats to water quantity and quality due to enhanced climate variability and change. At an operational level, current water allocation systems do not take into account state-of-the-art climate forecasting methods. Therefore, it is often not until after the irrigation season is well underway that irrigators have a reasonable knowledge of how much water will be available. Thus, there is considerable risk associated with planting and crop establishment decisions, resulting in a need for climate forecasting tools aimed at risk management. There is also a need for Australian water legislation and policy to be revisited to incorporate climate change and adaptive management options.

Perhaps the most significant example of adaptive management from Australia is the 2005 environmental watering of the Barmah-Millewa Forest in the Murray Darling Basin. As spring 2005 marked the 5th year since the previous significant spring flooding of the forest, a 5th year flooding rule was triggered. At the time, the decision to release over 500 GL of water from storage during a significant drought period was very difficult and contentious for senior managers and politicians. The perceived high cost of returning water to the environment was such that it had to be carefully justified. Some of the Murray-Darling River system was already under declared drought conditions and inflows into the storages that year were only average. In retrospect, the tangible ecological benefits of this decision were entirely demonstrated to all stakeholders, including enhanced native fish spawning and recruitment. Moreover, the drought has continued and worsened as it is now in its 10th year. If the 2005 environmental water allocation release had not occurred, the Barmah-Millewa Forest and many other wetlands along the River Murray that also benefited from the release may well have been damaged irreversibly (King et al., 2010).

4.4. Key challenges from a policy perspective

Priority areas for action and further research/investigation include:

- The need for a focus on sustainable basin management that includes environmental flows (to increase social and economic resilience downstream), upper watershed management (to buffer climate risks), and building water governance capacity (to enable integrated and adaptive water management in a changing climate).
- The need to make more tangible and recognise natural or green infrastructure and the services provided by ecosystems to society, and the need for freshwater to preserve those ecosystems. The value of natural infrastructure should be included in investment priorities and plans together with the development of tools to determine the value, needs and preservation approaches for natural infrastructure.
- Developing experience in awareness raising on drought across sectors and the public to understand the risks of drought and the possible management options. Stakeholder involvement and community participation can be important to legitimate and mobilise against ad-hoc drought management and is foreseen by the Water Framework Directive.
- Drought planners may fail to determine which drought-related environmental impacts can be tolerated and which cannot. Appropriate drought impact-reduction measures are required based on sound and agreed data that is regionally, nationally, and basin-wide applicable (recognising that droughts are inter-basin and may be transboundary in nature).
- Restoration of degraded ecosystems should be included as part of planning for watershed or river basins because many of these concerns extend across human drawn boundaries and borders (e.g.: transboundary groundwater impacts etc).
- Further investigation into the current entry points in drought monitoring systems (existing and those currently under development) for integrating multidisciplinary information for the development of drought based environmental indicators (U.N., 2003; 2007).

- Improvement in hydrological monitoring recognising the changing climate, possible increase in extremes (drought and flood) and multidisciplinary indicators required for drought monitoring (from an impact perspective). For example, whether environmental flows can be used to define thresholds and indicators for low flows as a limiting factor for vegetation.
- Recognition of the capacity development needs to renew hydrological sciences and other primary institutions responsible for monitoring climate and hydrology (established under the concept of climate 'stationarity'). This is of primary concern to operational water managers who need to manage reservoirs, dams, rivers, and groundwater, within an ecosystem context to maintain services to multiple users, whilst working on water use efficiency and demand management approaches. Often these practices are based on extrapolated hydrological data basin-wide. The management complexities will increase, and supporting systems and finance will be required in the future. This includes looking at space based technologies to understand basin wide climate effects better, and to integrate this with multidisciplinary databases to fully understand the detrimental effects of droughts on ecosystems, and therefore the services they provide.
- Can initial steps be made on streamflow thresholds for operational use in existing basins where drought has already occurred? Can we move beyond the need for agreed scientific definitions initially to learn from approaches and refine as they develop? Some countries may not have the luxury of research skills and funding on drought, yet they face more regular drought events.
- Multidisciplinary scientific programmes are required to understand and plan for drought (recognising the role of new science areas such as ecohydrology etc to understand feedback mechanisms). This should include practical field level operators and can help articulate on how pressures other than climate change holistically interact with drought in terms of thresholds, regime shifts and feedback loops.
- Investigate the role of environmental flows for river basin allocation to improve the resilience of ecosystems to drought. Environmental Flows will need to be nationally determined based on the WFD requirement to maintain good ecological status. There is a need to strengthen models and approaches for measuring low flows, including general rules or coping mechanisms that apply to the different climatic conditions.
- Rationalise tools for environmental flows to develop a suite of approaches relevant to river basins in Europe and integrate their use into basin interventions through SEA regulatory instruments.
- Investigate the role of payments for ecosystem services as a mechanism to distinguish the role of ecosystem services in society and to provide revenue (both financial and through employment provision) for ecosystem restoration and maintenance to provide water and maintain the ecosystem through drought periods. This may include the role of agriculture as a provider of environmental services such as groundwater recharge in the event of overallocation from river abstractions.
- Further research may be required on the cost of droughts and the negative impacts on ecosystems in relation to tourism revenue. Areas damaged, perhaps irreversibly, during droughts may not be tourism hot spots in the future.
- Strengthen river basin management plans with areas identified as refugia during different drought strength and return periods. Aquatic plants and animals in ephemeral streams use drought refuges to survive stream drying. This is the ecological feature that distinguishes them from perennial watercourses and the management of refuges must be included in any water resources planning and management (Robson, 2008).

- Fluvial systems are highly dynamic and respond to changes in flows and water levels in complex ways. Morevoer, changes caused by human impacts can be cumulative and sometimes irreversible e.g. loss of species (Petts, 2008). System reactions should be also considered as non-liner rather than step-wise processes

- The principle of stationarity should be abandoned from both a science and management perspective. From a scientific perspective, advances are required to integrate human and environmental water needs in river management through commitment to long-term research designed to better describe abiotic–biotic responses (compare research gaps in Section 2). The incorporation of climate variations, cycles of channel change, and improved population models over decadal timescales is needed to advance realistic models of riverine ecosystems. From a management perspective, there is still attention to maximizing economic yield and a belief that technology can provide the solution to environmental risks. To educate politicians and the public about the importance of variability in sustaining riverine ecosystems, including droughts, is a major challenge that remains to be addressed (Petts, 2008).

5. Relevance to Water Framework Directive

The European Union has agreed upon a common policy on water in the Water Framework Directive (henceforth: WFD). The WFD stipulates that Member States must have prepared plans by the end of 2009. River Basin Management Plans must be made for each and every river basin within the territories of the Member States, and in those situations that river basins are shared by more than one Member State, the states involved have to cooperate and make joint plans. A river basin is congruent with the hydrological unit defined by a river system. Within the framework of the present discussion, the question arises to what extent droughts, or more accurate, water scarcity management, is part of the plans. Equally important is the question how appropriate the River Basin Management Plans are as instruments to deal with the effects of droughts and water scarcity. Elsewhere in this document, the conclusion was drawn that drought complicate efforts to maintain good water quality. For example it was said that water managers try to keep water levels in selected reservoirs high during droughts, in an effort to meet water demand. The consequence is that water quality in other bodies of water will be compromised. The need for minimum environmental flows was mentioned, as a means to guarantee overall minimally-required water quality in a river basin. This section of the report addresses how the findings on the impact of droughts on the environment related to the details of the WFD.

5.1. Drought in the Water Framework Directive

The WFD is by far the most important piece of European Union legislation on water. The European Union adopted the WFD in October 2000 (European Union, 2000). By doing so, the principle of uniform water management throughout Europe was introduced. In the context of the present discussion it is important to note that the main objective of the WFD is to manage water quality: to achieve good ecological and chemical status of surface water bodies, and chemical and quantitative status of groundwater. The directive creates a framework for protecting water resources with the goals of protecting ecosystems and improving the aquatic environment. Article 1.e of the WFD states the 'need to mitigate the effects of floods and droughts'. Drought management and water scarcity management are not primary objectives of the WFD, as was explained above. The 'need to mitigate the effects of floods and droughts' must be understood in relation to the WFD's main objective to maintain good water quality. Water scarcity is only an issue because under conditions of water scarcity maintaining good ecological and chemical status of water bodies and chemical and quantitative status of groundwater will be more difficult. It is for this reason that the WFD makes the only exception to the requirement to maintain good water quality everywhere and always within the European Union. Preamble 32 of the WFD states that prolonged droughts are "… grounds for exemptions from the requirement to prevent further deterioration and to achieve good status". It is further stated that measures that directly relate to drought mitigation are left as optional supplementary measures (WFD Annex VI, Part 5).

5.2. River Basin Management Plans

The cornerstone of the WFD is the above-mentioned requirement for River Basin Management Plans. The first edition of the River Basin Management Plans has to be ready by the end of 2009; the plans are to be reviewed in 2016. The WFD prescribes in detail the requirements to which the River Basin Management Plans are to comply. Article 13 of the WFD contains the instruction to prepare River Basin Management Plans. It refers to Annex VII for the list of topics that are to be included in the River Basin Management Plans. It appears that the instructions are strictly followed by the Member States. The internet was used to get access to examples of River Basin Management Plans that were produced in accordance with the European Union requirement. The plans for the following river systems were analyzed: Rhine (French, Germany, Luxemburg, Swiss, The Netherlands), Danau (Germany, Austria, Check Republic, Slovakia, Hungary, Croatia, Montenegro, Serbia, Bosnia-Herzegovina, Romania, Bulgaria,Moldova, Ukrain), Po (Italy), Ebro (Spain), Nestos (Greece), Strymonas (Greece), and a set of "Anglia" river basins (Great Britain). More examples could be found and analyzed, but that is hardly necessary, given the overall conclusion that each River Basin

Management Plans follows exactly the instructions of the WFD. That means that each River Basin Management Plans starts with a description of the physical situation (description of the surface water bodies and groundwater reservoirs), and continues with describing the pressures because of human activities, the mapping of protected areas, the monitoring networks in place, the environmental objectives, the economic analyses of water use, the program of measurements, the way that stakeholders were consulted, and a number practicalities. The outline of the River Basin Management Plans as required by the WFD gives one opening for adding more detailed programmes to deal with specific conditions. This is Article 13.5, which states that "River basin management plans may be supplemented by the production of more detailed programmes and management plans for sub-basin, sector, issue, or water type, to deal with particular aspects of water management". A drought would be an 'issue' in the sense of Article 13.5. The WFD does not give any further specifications. On the contrary, one would say, as Annex VII.8. says that River Basin Management Plans only need to provide a list of such more detailed programmes. Additional programmes are not only provided on a voluntary basis, but only need to be mentioned also.

5.3. The Water Framework Directive and environmental flows

One of the more important conclusions (recommendations) reached by the Environmental Impact Group in this Background Document is that a minimum flow should be maintained in river basins as a practical means to maintain water quality throughout the river basin. After all, if water bodies within a river basin remain interconnected even during droughts, it would be easier to manage water levels in water bodies. Managing water levels is an important way of managing water quality. If a water body becomes isolated and its water level drops, the concentration of the substances that define water quality becomes less optimal. If water bodies remain connected, it would at least in theory be possible to drain off low quality water and to add water of higher quality, and in the process to increase water levels in every water body in a basin. The question presents itself whether the prescribed structure for the River Basin Management Plans accommodates this requirement, and if so, where specifically. Section 7.10 of the River Basin Management Plans would be the place to do so: a River Basin Management Plans shall include details of the "supplementary measures identified as necessary in order to meet the environmental objectives established". Looking back again at the River Basin Management Plans that were analyzed, however, it appears that none of them contain measures of the kind that is recommended. That should not come as a surprise, as the subject of drought is also not receiving specific attention in the plans either.

Acreman and Ferguson (2010) also point out that, whilst the WFD explicitly requires stakeholder involvement, national government agencies have interpreted this as largely a dissemination exercise. As ecological objectives are pre-set in the WFD, stakeholders are de facto no longer involved in negotiation over these. However, stakeholders may have an opportunity to be more involved in reviewing environmental standards for water resources. This can entail the dual responsibility to define water abstraction limits that maintain a healthy river ecosystem and ecologically appropriate flow releases from reservoirs. On the one hand, WFD does not specify how water for environmental flows may be retrieved where its over-use has been licensed. On the other hand, each Member State has its own existing tools and data for setting environmental flows and water management. Ultimately, agreeing to the measures adopted to restore river ecosystems to the status required by the WFD would equal to endorse RBMPs.

5.4. The Water Framework Directive and wetlands

The directive institutionalizes ecosystem-based objectives and planning processes at the level of the river basin as the basis for water resource management. These objectives include achieving both good ecological and chemical status for surface waters and good chemical and quantitative status for groundwater. Implementing environmental flows will thus be a key measure for restoring and managing river ecosystems. Less explicit, but no less important are objectives for wetlands. Wetland ecosystems will play a key role both in terms of specific WFD objectives and in appropriate circumstances in terms of the programmes of measures to meet broader objectives through wetland creation and enhancement (e.g. for pollution abatement and flood protection).

Good groundwater chemical status is set out in Annex V (2.3.2) under Article 2 (25) and includes preventing a significant deterioration of the ecological or chemical quality of associated surface waters, or any significant damage to terrestrial ecosystems which depend directly on groundwater (groundwater dependent terrestrial ecosystems or GWDTEs). Similarly good groundwater quantitative status is set out in Annex V (2.1.2) under Article 2 (28) and includes preventing a significant deterioration in the status of associated surface waters or GWDTE. It is therefore important to examine the different wetland types in the context of defining River Basin D boundaries and in the delineation of their catchment areas for risk assessment as required by Articles 3 and 5, respectively of WFD. Where a Natura 2000 Protected Area forms part of a water body or where a water body lies within a Natura 2000 Protected Area, the WFD status objectives apply in addition to the requirement to maintain at ‘favourable conservation status’ or restore it to that status. Some water bodies that coincide with Natura 2000 Protected Areas have been designated as artificial or heavily modified. In these cases the aim to achieve good ecological potential applies in addition to the objective of ‘favourable conservation status’. Although the WFD requires the development of River Basin Management Plans by 2009 and water-dependent Natura 2000 sites have to reach ‘good ecological status’ by 2015, there is some consensus that WFD objectives should be considered a more stringent standard than ‘favourable conservation status’ as per Habitats Directive.

If a wetland has been identified as a discrete and significant water body, the objectives will be the same as for other water bodies as set out in Article 4 of the WFD. If the wetland has not been identified as a water body but forms part of the hydro morphological quality element zone of a surface water body, then wetlands which comprise part of the hydro morphological quality element zone of a surface water body must be in a condition that is consistent with the required ecological status (Annex V - 1.1). The WFD prescribes that achieving good groundwater status includes preventing impact on associated surface waters or GDTE which will include wetlands such as turloughs and fens (Annex V - 2.1.2 and 2.3.2). Most importantly, if a wetland has been included in the register of protected areas, specific obligations under the Habitats (92/43/EEC) and Birds (79/409/EEC) Directives apply.

5.5. Conclusions and recommendations

As can be concluded from the above, there would be scope for dealing with droughts in the River Basin Management Plans. It would also be possible to describe in the plans themselves specific measures that will be taken in case of a drought. This leaves unanswered the question whether the River Basin Management Plans would be the most appropriate place to accommodate drought plans. This question is more difficult to answer. It would first require an answer to the question what should be in the drought plans. Also, River Basin Management Plans are made for every river basin and river basins are very different from each other, for example in size. That also needs to be considered when answering the question how drought management should relate to the WFD and to River Basin Management Plans.

Another important consideration is whether targeting ‘good ecological status’ for most waterbodies, and the process of waterbody classification at large, is an adequate approach to drought management. As set out by the WFD, the concept appears too sophisticated for catching politicians’ and the public’s attention. As a matter of fact, there are more visible impacts of drought on streams such as extensive fish kills or toxic algal blooms than the changes in fish, invertebrates and algae communities at which the biological reference condition refer to. Moreover, there is perhaps enough detail on the consequences of drought for fish or macro-invertebrates but very few tools available for water resource managers to evaluate the overall impacts at the river basin level.

Other relevant recommendations for the research agenda that have arisen from a policy and management perspective include developing common sets of ecological indicators for at least countries with a similar climate, enhance stakeholder involvement and community participation in order to legitimate and mobilize against ad-hoc drought management, and demonstrate that the linkage between resilience of ecosystems and socio-economic systems is critical for IWRM to be deployed as a strategy for reducing drought vulnerability.

6. References

Acreman, M.C., and Dunbar, M.J., 2004. Methods for defining environmental flow requirements – a review. Hydrology and Earth System Sciences. 8(5): 861-876.

Adams, S.B. and Warren, M.L., 2005. Recolonisation by warmwater fishes and crayfishes after severe drought in upper coastal plain hill streams. Transactions of the American Fisheries Society 134(5), 1173-1192.

Aherne, J., Larssen, T., Cosby, B.J., and Dillon, P.J., 2006. Climate variability and forecasting surface water recovery from acidification: Modelling drought-induced sulphate release from wetlands. Science of the Total Environment, 365:186-199.

Allen, C.D. Macalady, A.K. Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A.. Breshears, D.D., Hogg, E.H., Gonzalez, P, Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J-H. Allard, G., Running, S.W., Semerci, A. and Cobbt, A., 2009. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. Forest Ecology and Management 259(4): 660-684.

Ambrosetti, W., Barbanti, L., and Rolla, A., 2006. The climate of Lago Maggiore area during the last 50 years. Journal of Limnology, 65(1), 62 pp.

Anderson, J. ed., 2008. Climate change-induced water stress and its impact on natural and managed ecosystems. Study for the European Parliament's Temporary Committee on Climate Change: http://www.europarl.europa.eu/activities/committees/studies/download.do?file=19073

Angeler, D.G. and Alvarez-Cobelas, M., 2005. Island biogeography and landscape structure: Integrating ecological concepts in a landscape perspective of anthropogenic impacts in temporary wetlands. Environmental pollution 138, 420-424.

Archaux, F. and Wolters V., 2006. Impact of summer drought on forest biodiversity: what do we know? Annals of Forest Science 63, 645-652.

Arnell, N.W. 1999. Climate change and global water resourrses. Global Environmental Change 9, 31-49.

Arthington, A.H. and Pusey, B.J., 2003. Flow restoration and protection in Australian rivers. River Research and Applications 19 (5-6): 377-395.

Atkinson, B., Spooner, D.. Treadwell, S. and Bills, M. (2008). When environmental flows go wrong: A case study demonstrating the importance of understanding the inter-relationship between flow components in the Loddon River, Victoria. In. "Keeping aquatic ecosystems on Australia's water management agenda ". Proceedings of the 47th ASL Congress, Mandurah Western Australia, 29 September – 3 October 2008.

Barber, T., Bounds, A., Burnett, V., Cienski, J., Harvey, F., Hollinger, P., and Wiesmann, G., 2006. Drought-stricken Europe verging on 'natural disaster'. Financial times, August 10.

Battarbee, R., Kernan, M., Livingstone, D., Moss, B., George, G., Jeppesen E., Johnson, R., Wright, D., Hering, D., Verdonschot, P., Maberly, S., Whitehead, P., Maltby, E., Skeffington, R., Catalan, J., Grimalt, J.O., Nickus, U., Forsius, M., Horlitz, T., Gessner, M., Jenkins, A., Psenner, R., Lyche-Solheim, A., and Verhoeven, J., 2008. Euro-limpacs Position Paper - Impact of climate change on European freshwater ecosystems: consequences, adaptation and policy. Deliverable No. 301. Euro-limpacs project, GOCE-CT-2003-505540.

Bates, B.C., Z.W. Kundzewicz, S. Wu and J.P. Palutikof, Eds., 2008. Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp. [http://www.ipcc.ch/pdf/technical-papers/climate-change-water-en.pdf]

Bayliss, B., Brenman, K., Elliot, I., Finlayson, M., Hall, R., House, T., Pidgeon, B., Walden, D. and Waterman, P. 1997. Vulnerability Assessment of Predicted Climate Change and Sea Level Rise in the Alligator Rivers Region, Northern Territory Australia. Supervising Scientist Report 123, Supervising Scientist, Canberra, 134 pp.

Beatley, T., 2000. Green Urbanism: Learning from European cities. Island Press, Washington D.C.

Bellot, J., Bonet, A., Sanchez, J.R., and Chirino, E., 2001. Likely effects of land use changes on the runoff and aquifer recharge in a semiarid landscape using a hydrological model. Landscape and Urban Planning. 55(1): 41-53.

Begzsurena, S., Ellis, J.B., Ojimab, D.S., Coughenourb, M.B. and Chuluunb, T., 2004. Livestock responses to droughts and severe winter weather in the Gobi Three Beauty National Park, Mongolia. Journal of Arid Environments 59, 785–796

Beniston, M. and H.F. Díaz, 2004. The 2003 heatwave as an example of summers in a greenhouse climate? Observations and climate model simulations for Basel, Switzerland. Global Planet. Change, 44, 73–81.

Bennun, L., Matiku, P., Mulwa, R., Mwangi, S. and Bucley, P., 2005. Monitoring Important Bird Areas in Africa: Towards a Sustainable and Scaleable System. *Biodiversity and Conservation 14*(11), 2575-2590.

Bergkamp, G., 1998. Hydrological processes affecting the resilience of Quercus spp dominated geoecosystems in central Spain. Geomorphology, 23: 101 - 126.

Bird, P.R., 1998. Tree windbreaks and shelter benefits to pastures in temperate grazing systems. Agroforestry Systems 41: 35-54.

Bird, P.R., Bicknell, D., Bulman, P.A., Burke, S.J.A., Leys, J.F., Parker, J.N., van der Sommen, F.J. and Voller, P., 1992. The role of shelter in Australia for protecting soils, plants and livestock. Agroforestry Systems 18: 59-86.

Black, E., M. Blackburn, G. Harrison, B. Hoskins, and J. Methven, 2004. Factors contributing to the summer 2003 European heatwave. Weather, 59, 217–221.

Blake, W.H., Wallbrink, P.J., and Droppo, I.G., 2009. Sediment aggregation and water quality in wildfire-affected river basins. Marine and Freshwater Research, 60(7): 653-65.

Bond, N. R., Lake, P. S. and Arthington, A. H., 2008. The impacts of drought on freshwater ecosystems: an Australian perspective. Hydrobiologia 600, 3-16.

Bond, N., 2007. Identifying, mapping and managing drought refuges: a brief summary

of issues and approaches. eWater Technical Report. eWater Cooperative Research Centre, Canberra. http://ewatercrc.com.au/reports/Bond-2007-Drought_Refuges.pdf

Boulton A.J., 1989. Over-summering refuges of aquatic macroinvertebrates in two intermittent streams in central Victoria. *Transactions of the Royal Society of South Australia 113*: 23-34.

Boulton A.J. and Lake P.S., 1992. The ecology of two intermittent streams in Victoria, Australia II: Comparisons of faunal composition between habitats, rivers and years. *Freshwater Biology 27*:99-121.

Boulton A.J. and Lake P.S., 1992. The ecology of two intermittent streams in Victoria, Australia III: Temporal changes in faunal composition. *Freshwater Biology 27*: 123-138.

Boulton, A.J., 2003. Parallels and contrasts in the effects of drought on stream macroinvertebrate assemblages, Freshwater Biology, 48 (7), 1173-1185.

Brock, M.A., Nielsen, D.L., Russell, J.S., Green, J.D. and Langley, J.D., 2003. Drought and aquatic community resilience: the role of eggs and seeds in sediments of temporary wetlands. Freshwater Biology 48(7), 1207-1218.

Brown, L.E., Hannah, D.M. and Milner, A.M., 2005. Spatial and temporal water column and streambed temperature dynamics within an alpine catchment: Implications for benthic communities. Hydrological Processes 19 (8), pp. 1585-1610.

Bunn, S.E., Thoms, M.C., Hamilton, S.K., and Capon, S.J., 2006. Flow variability in dryland rivers: boom, bust and the bits in between. River Research Applications 22, 179-186.

Burkholder JM, Dickey DA, Kinder CA, Reed RE, Mallin MA, McIverMR, et al., 2006. Comprehensive trend analysis of nutrients and related variables in a large eutrophic estuary: a decadal study of anthropogenic and climatic influences. Limnol. Oceanogr.51:463–87.

Byrne R.A. and McMahon R.F., 1994. Behavioral and physiological responses to emersion in freshwater bivalves. *American Zoologist* 34: 194-204.

Caissie, D., 2006. The thermal regime of rivers: a review. Freshwater Biology, 51, 1389–1406.

Carpenter, S.R., 2003. Regime Shifts in Lake Ecosystems: Pattern and Variation. Excellence in Ecology Series 15. Oldendorf/Luhe, Germany: Ecology Institute.

Caruso, B.S., 2002. Temporal and spatial patterns of extreme low flows and effects on stream ecosystems in Otago, New Zealand. Journal of Hydrology 257, 115–133.

CCR., 2007. Natural disasters in France. Caisse Centrale de R´eassurance, Paris, 24 pp.

Chambers, R. and Conway, G., 1992. Sustainable rural livelihoods: Practical concepts for the 21st century. IDS Discussion Paper 296. Brighton: Institute for Development Studies.

Charman, D., 2002. Peatlands and Environmental Change. Wiley, Chichester.

Chow, A.T., Tanji, K.K., and Gao,S., 2003. Production of dissolved organic carbon DOC and trihalomethane prescurso THM from peat soils. Water Resources, 37:4475-4485.

Ciais, P., M. Reichstein, N. Viovy, A. Granier, J. Ogee, V. Allard, M. Aubinet, N. Buchmann, et al., 2005. Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature, 437, 529–533.

Clair, T.A., Ehrman, J.M., 1996. Variations in discharge and dissolved organic carbon and nitrogen export from terrestrial basins with changes in climate: a neural network approach. Limnology and Oceanography 41, 921–927.

Closs, G.E. and Lake, P.S., 1996. Drought, differential mortality and the coexistence of a native and an introduced fish species in a south east Australian intermittent stream. *Environmental Biology of Fishes 47*(1):, 17-26.

Cooley, H., Christian-Smith, J., and Gleick, P., 2009. Sustaining California Agriculture in an Uncertain Future. Pacific Institute, Oakland, California. U.S.A.

Commission of the European Communities, 2009. Climate Change and Water, Coasts and Marine Issues. Commission Staff Working Document accompanying the White Paper, Adapting to Climate change: Towards a European Framework for Action. Brussels, 01/04/09, SEC(2009) 386.

Cork, S.J. and Shelton, D., 2000. The nature and value of Australia’s ecosystem services: A framework for sustainable environmental solutions. In “Sustainable environmental solutions for industry and government.” Environmental Engineering Society, Queensland Chapter, The Institution of Engineers, Australia, Queensland Division, and Queensland Chamber of Commerce and Industry, pp151-159.

Correll DL, Jordan TE and Weller DE. Effects of interannual variation of precipitation on stream discharge from Rhode River subwatersheds. J. Am. Water Resour. Assoc. 1999;35:73–82.

Corti, T., Muccione, V., Köllner-Heck, P., Bresch, D. and Seneviratne, S.I., 2009. Simulating past droughts and associated building damages in France. Hydrol. Earth Syst. Sci., 13, 1739–1747.

Covich, A.P., Palmer, M.A., and Crowl, T.A., 1999. The role of benthic invertebrate species in freshwater ecosystems. BioScience 49: 119-127.

Craig, R.K., 2007. Climate Change, Regulatory Fragmentation, and Water Triage. ExpressO Available [Online]: http://works.bepress.com/robin_craig/2

Dahm, C.N., Baker, M.A., Moore, D.I., and Thibault, J.R., 2003. Coupled biogeochemical and hydrological responses of streams and rivers to drought. Freshwater Biology, 48, 1219–1231.

Daily, G. E., 1997. Nature's Services – Societal Dependence on Natural Ecosystems. Island Press, Washington

Darwell, W.R.T. and Vié, J.-C., 2005. Identifying important sites for conservation of freshwater biodiversity: extending the species-based approach. *Fisheries Management and Ecology 12*, 287–293.

Davey, A.J.H. and Kelly, D.J., 2007. Fish community responses to drying disturbances in an intermittent stream: a landscape perspective. Freshwater Biology, doi:10.1111/j.1365-2427.2007.01800.

Dayton PK, Tegner MJ, Edwards PB and Riser KL. Sliding baselines, ghosts, and reduced expectations in kelp forest communities. Ecol. Appl. 1998;8:309–22.

De Groot C.J. and Van Wijck C., 1993. The impact of desiccation of a freshwater marsh (Garcines Nord, Camargue, France) on sediment-water-vegetation interactions. *Hydrobiologia 252*: 83-94.

Department of Health (2008) Health effects of climate change in the UK, 2008. an update of the Department of Health report 2001/2002. Department of Health.

Dickens C., Kotze D., Mashigo S., MacKay H., and Graham M., 2004. Guidelines for integrating the protection, conservation and management of wetlands into catchment management planning. Water Research Commission Report Number TT220/03, Pretoria, South Africa. Available on request from the Water Research Commission www.wrc.org.za.

Dillon, P.J., Molot, L.A., and Futter, M., 1997. The effect of El-Nino related drought on the recovery of acidified lakes. Environ. Monit. Assess., 46:105-111.

Doering, M., Uehlinger, U., Rotach, A., Schlaepfer, D.R. and Tockner, K., 2007. Ecosystem expansion and contraction dynamics along a large alpine alluvial corridor (Tagliamento river, North East Italy) Earth Surface Processes and Landforms 32 (11), pp. 1693-1704.

Drexler, J.Z. and Ewel, K.C., 2001. ENSO-related drought on hydrology and salinity in a Micronesian wetland complex. Estuaries 24(3), 347-356.

Ducharne, A., Baubion, C., Beaudoin, N., Benoit, M., Billen, G., Brisson, N., Garnier, J., Kieken, H., Lebonvallet, S., Ledoux, E., Mary, B., Mignolet, C., Poux, X., Sauboua, E., Schott, C., Thiery, S., and Viennot, P., 2007. Long term prospective of the Seine River system: Confronting climatic and direct anthropogenic changes, Sci. Total Environ., 375, 292–311, doi:10.1016/j.scitotenv.2006.12.011.

Ducharne, A., 2008. Importance of stream temperature to climate change impact on water quality. Hydrol. Earth Syst. Sci., 12, 797–810.

Dunbar, M.J., Pedersen, M.L., Cadman, D. Extence, C., Waddingham, J., Chadd, R., Larsen, S.E., 2010. River discharge and local-scale physical habitat influence macroinvertebrate LIFE scores. Freshwater Biodiversity 55(1): 226-242

Easterling DR, Meehl GA, Parmesan C, Changnon SA, Karl TR, Mearns LO., 2000. Climate extremes: observations, modelling, and impacts. Science;289:2068–74.

Edgar GJ, Bustamante RH, Fariña JM, Calvopiña M, Martínez C, Toral-Grande MV, 2004. Bias in evaluating the effects of marine protected areas: the importance of baseline data for the Galapagos Marine Reserve. Environ. Conserv., 31:212–8.

EEA, 2001. Sustainable water use in Europe - Part 3: Extreme hydrological events: floods and droughts. Environmental issue report No 21

EEA. 2009. Regional climate change and adaptation: The Alps facing the challenge of changing water resources. European Environment Agency Technical Report No.9/2009.

EEA. 2010. 10 messages for 2010: Climate change and biodiversity. European Environment Agency, Copenhagen.

Elliott J.M., 2006. Periodic habitat loss alters the competitive coexistence between brown trout and bullheads in a small stream over 34 years. *Journal of Animal Ecology 75:* 54-63.

Elliott, J.M., 2000. Pools as refugia for brown trout during two summer droughts: trout responses to thermal and oxygen stress. Journal of Fish Biology, 56, 938–948

Elmqvist, T., Folke, C., Nyström, M., Peterson, G., Bengtsson, J., Walker, B., and Norberg, J., 2003. Response diversity and ecosystem resilience. Frontiers in Ecology and the Environment 1(9), 488–494.

Elsdon, T.S., De Bruin M.B.N.A. , Diepen, N.J., Gillanders, B.M., 2009. Extensive drought negates human influence on nutrients and water quality in estuaries. Science of the Total Environment 407 (2009), 3033–3043.

European Commission, 2003. Water *Framework Directive Common Implementation Strategy Guidance Document No 12 – Horizontal Guidance on the Role of Wetlands in the Water Framework Directive.* European Communities, Luxembourg Available [online]: http://circa.europa.eu/Public/irc/env/wfd/library?l=/framework_directive/guidance_documents/guidance_wetlands/_EN_1.0_&a=d

European Commission, 2007. Drought Management Report of the Water Scarcity and Droughts Expert Network including Agricultural, Drought Indicators and Climate Change Aspects. European Communities, Luxembourg. Available [online]: http://ec.europa.eu/environment/water/quantity/pdf/dmp_report.pdf

Evans, C.D., Reynolds, B., Hinton, C., Hughes, S., Norris, D., Grant, S., and Williams, B., 2008. Effects of decreasing acid deposition and climate change on acid extremes in an upland stream. Hydrol. Earth Syst. Sci., 12, 337–351.

Falkenmark, M., and Folke, C., 2002. The ethics of socio-hydrolological catchment management: Towards Hydrosolidarity. Hydrology and Earth System Sciences, 6:1-9.

Fang, X, and Pomeroy, J.W., 2008. Drought impacts on Canadian prairie wetland snow hydrology. Hydrological Processes 22, 2858-2873.

FAO, 1985. Livestock losses and post-drought rehabilitation in Sub-Saharan Africa. LPU Wroking Paper, FAO, Rome, Italy. Available [online]: http://www.fao.org/ wairdocs/ILRI/x5439E/x5439e00.htm

Fink, A.H., T. Brücher, A. Krüger, G.C. Leckebusch, J.G. Pinto, and U. Ulbrich, 2004. The 2003 European summer heatwaves and drought: synoptic diagnosis and impacts. Weather, 59, 209–216.

Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L. and Holling, C.S., 2004. Regime Shifts, Resilience, and Biodiversity in Ecosystem Management. Annual Review of Ecology, Evolution, and Systematics 35, 557-581.

Forslund, A., et al., 2009. Securing Water for Ecosystems and Human Well-being: The Importance of Environmental Flows. Swedish WaterHouse Report 24. SIWI, Stockholm.

Fukushima, T., Ozamki, N., Kaminishi, H., Harasawa, H., Matsushige, K., 2000. Forecasting the changes in lake water quality in response to climate changes, using past relationships between meteorological conditions and water quality. Hydrological Processes 14, 593–604.

Furey P.C., Nordin R.N. and Mazumder A., 2006. Littoral benthic macroinvertebrates under contrasting drawdown in a reservoir and a natural lake. *Journal of the North American Benthological Society 25*: 9-31.

Gagnon P.M., Golladay S.W., Michener W.K. and Freeman M.C., 2004. Drought responses of freshwater mussels in Coastal Plain tributaries of the Flint River basin, Georgia. *Journal of Freshwater Ecology 19*: 667-679.

Gellens, D. and Roulin, E., 1998. Streamflow response of Belgian catchments to IPCC climate change scenarios. Journal of Hydrology 210, 242–258.

George, A., 2005. Watering patterns for floodplain eucalypts. Watershed, 15.

Gilbert, B., Dillon, P.J., Somers, K.M., Reid, R.A., Scoot, L., 2008. Response of benthic macroinvertebrate communities to El Nino related drought events in six upland streams in south-central Ontario. Can. J. Fish Aquat. Sci., 65:890-905.

Gill. S., 2004. The Ecosystem Approach: Five Steps to Implementation. IUCN, Gland, Switzerland and Cambridge, UK. vi + 30 pp.

Gjerlov, C., Hildrew, A.G. and Jones, J.I., 2003. Mobility of stream invertebrates in relation to disturbance and refugia: a test of habitat templet theory. Journal of the North American Benthological Society 22: 207–223.

Gómez, R., Hurtado, I., Suarez, M.L., et al., 2005. Ramblas in south-east Spain: threatened and valuable ecosystems, Aquatic Conservation-Marine And Freshwater Ecosystems, 15 (4), 387-402.

Gómez-Rodríguez, C., Díaz-Paniagua, C., Serrano, L., Florencio, F. and Portheault, A., 2009. Mediterranean temporary ponds as amphibian breeding habitats: the importance of preserving pond networks. Aquatic Ecology 43(4): 1179-1191.

Gosse, Ph., Gailhard, G., Hendrickx, F., 2008. Analyse de la température de la Loire moyenne en été sur la période 1949 à 2003 Analysis of the mid-Loire temperature in summer (1949-2003). Hydroécologie Appliquée, 16 (2008), 233-274.

Greater London Authortiy, 2008. The London Climate Change Adaptation Strategy. The Greater London Authority.

Greaves, J.H., 1989. Rodent pests and their control in the Near East. FAO Plant Production and Protection Paper,No.95. Food and Agricultural Organization of the United Nations, Rome.

Grillas, P., Gauthier, P., Yavercovski, N. and Perennou, C., 2004. Les mares temporaries Méditerranéennes. Volume 1 – Enjeux de conservation, fonctionnement et gestion. Station biologique de la Tour du Valat, Arles, France Available [online]: http://ec.europa.eu/environment/life/project/Projects/files/brochure/Guide_gestion_vol1_TourValat.pdf

Gunderson, L.H., 2001. South Florida: the reality of change and the prospects for sustainability - Managing surprising ecosystems in southern Florida. Ecological Economics 37, 371–78.

GWP/INBO, 2009. A Handbook for Integrated Water Resources Management in Basins. http://www.oieau.fr/IMG/pdf/GWP-INBOHandbookForIWRMinBasins.pdf

Haberl, H., V. Winiwarter, K. Andersson, R. U. Ayres, C. Boone, A. Castillo, G. Cunfer, M. Fischer-Kowalski, W. R. Freudenburg, E. Furman, R. Kaufmann, F. Krausmann, E. Langthaler, H. Lotze-Campen, M. Mirtl, C. L. Redman, A. Reenberg, A. Wardell, B. Warr, and H. Zechmeister, 2006. From LTER to LTSER: conceptualizing the socioeconomic dimension of long-term socioecological research. Ecology and Society 11(2): 13. Available online: http://www.ecologyandsociety.org/vol11/iss2/art13/

Haigh, M. and Kilmartin, M.P., 2006. Hydrology of disturbed peatland, Heads of the Valleys, Wales. In: Environmental Role of Wetlands in Headwaters. Springer, Netherlands.

Hakala, J.P. and Hartman, K.J., 2004. Drought effect on stream morphology and brook trout (Salvelinus fontinalis) populations in forested headwater streams. Hydrobiologia 515: 203–213, 2004.

Hannah, D.M., Wood, P.J., and Sadler, J.P., 2004. Ecohydrology and hydroecology: A 'new paradigm'? Hydrological Processes, 18:3439-3445.

Heath, B.A., Maughan, J.A., Morrison, A.A., Eastwood, I.W., Drew, I.B., and Lofkin, M., 1999. The influence of wooded shelterbelts on the deposition of copper, lead and zinc at Shakerley Mere, Cheshire, England. The Science of the Total environment. Volume 235, Issues 1-3, 1 September 1999, Pages 415-417.

Hershey A.E., Shannon L., Niemi G.J., Lima A.R. and Segal R.R., 1999. *Prairie wetlands of southcentral Minnesota: Effects of drought on invertebrate communities* in D.P. Batzer, R.B. Rader and S.A. Wissinger (eds), Invertebrates in Freshwater Wetlands of North America: Ecology and Management, John Wiley and Sons, New York, pp. 515-541.

Hewes, W., 2008. Creating Jobs and Stimulating the Economy through Investment in Green Water Infrastructure. American Rivers and Alliance for Water Efficiency. Washington, DC.

Hill, T.D., and Polsky, C., 2007. Suburbanization and drought: A mixed methods vulnerability assessment in rainy Massachusetts. Environmental Hazards, 7 (4):291-301.

Hirji, R., and Davis, R., 2009. Environmental Flows in Water Resources Policies, Plans, and Projects. Findings and Recommendations. The International Bank for Reconstruction and Development/The World Bank. Washington, DC.

Hiwasaki, L., and Arioc, S., 2007. Integrating the social sciences into ecohydrology: facilitating an interdisciplinary approach to solve issues surrounding water, environment and people. Ecohydrology and Hydrobiology, (7)1:3-9.

Hole, D.G., Willis, S.G., Pain, D.J., Fishpool, L.D., Butchart, S.H.M., Collingham, Y.C., Rahbek, C., Huntley, B., 2009. Projected impacts of climate change on a continentwide protected area network. Ecology Letters *1*2, 420–431.

Holling, C.S., 1973. Resilience and stability of ecological systems. Annual. Review of Ecolgoy and Systematics 4, 1–23.

Hulme M, Barrow EM, Arnell NW, Harrison PA, Johns TC, Downing TE., 1999. Relative impacts of human-induced climate change and natural climate variability. Nature 1999;397:688–91.

Humphries, P. and Baldwin, D.S., 2003. Drought and aquatic ecosystems: an introduction. Freshwater Biology 48(7): 1141-1146

IPCC, 2000.. Special Report on The Regional Impacts of Climate Change - An Assessment of Vulnerability.

IPCC, 2007a. Working Group II Contribution to the Intergovernmental Panel on Climate Change (IPCC). Fourth Assessment Report Climate Change 2007: Climate Change Impacts, Adaptation and Vulnerability. Summary for Policymakers.

IPCC, 2007b. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Summary for Policymakers.

Isendahl, N., and Schmidt, G., 2006. Drought in the Mediterranean: WWF Policy Proposals. WWF/Adena, Madrid, Spain and WWF Mediterranean Programme, Rome, Italy.

James RT 1991, 'Microbiology and chemistry of acid lakes in Florida: I. Effects of drought and post-drought conditions', Hydrobiologia, vol. 213, pp. 205-225.

Jansson, P., R. Hock and T. Schneider, 2003. The concept of glacier storage: a review. J. Hydrol., 282, 116–129.

Johnson, W.C., Millet, B.V., Gilmanov, T., Voldseth, R.A., Guntenspergen, G.R., and Naugle, D.E., 2005. Vulnerability of Northern Prairie Wetlands to Climate Change- Bioscience, 55(10), 863-872.

Johnson, SL. 2003. Stream temperature: scaling of observations and issues for modelling. Hydrological Processes, 17, 497–499.

Journal Correio da Manha, 13-07-2005.

Kelley, K. F. 1986. Reservoir operation during drought: Case studies. Research Document No. 25, Hydrologic Engineering Center, U.S. Army Corps of Engineers, Davis, Calif.

Kelly, A.E., and Goulden, M.L., 2008. Rapid shifts in plant distribution with recent climate change. 105:33, 11823-11826, August 19, 2008. Proceedings of the National Academy of Sciences of the United States of America.

Kettunen, M, Terry, A., Tucker, G. and Jones A., 2007. Guidance on the maintenance of landscape features of major importance for wild flora and fauna - Guidance on the implementation of Article 3 of the Birds Directive (79/409/EEC) and Article 10 of the Habitats Directive (92/43/EEC). Institute for European Environmental Policy (IEEP), Brussels, 114 pp. & Annexes. Available [Online]:
http://ec.europa.eu/environment/nature/ecosystems/docs/adaptation_fragmentation_guidelines.pdf

Kilroy, G., Coxon, C., Ryan, J., O'Connor, A. and Daly, D., 2005. Groundwater and wetland management in the Shannon river basin (Ireland). Environmental Science and Policy 8(3): 219-225

King, A.J., Ward, K.A., O’Connor, P., Green, D., Tonkin, Z. and Mahoney J., 2010. Adaptive management of an environmental watering event to enhance native fish spawning and recruitment. Freshwater Biology 55(1): 17-31

Kirkby, M.J., Imeson, A.C., Bergkamp, G., Cammeraat, 1.H., 1996. Scaling up processes and models from the field plot to the watershed and regional areas. Journal of Soil & Water Conservation 51(5): 391-396.

Kosatsky T., 2005. The 2003 European heat waves. Euro Surveill., 10(7); available online: http://www.eurosurveillance.org/ViewArticle.aspx?ArticleId=552

Köppen, W., 1936. Das geographisca System der Klimate, in: Handbuch der Klimatologie, edited by: Köppen, W. and Geiger, G., 1. C. Gebr, Borntraeger, 1–44.

Kramer D.L., 1987. Dissolved oxygen and fish behaviour. *Environmental Biology of Fishes 18*: 81-92.

Kramer D.L. and McClure M., 1982. Aquatic surface respiration, a widespread adaptation to hypoxia in tropical freshwater fishes. *Environmental Biology of Fishes 7*: 47-55.

Krececk, J. and Haigh, M.J., 2006. Headwater wetlands. In: Environmental Role of Wetlands in Headwaters. Springer, Netherlands.

Krysanova, V., Hattermann, F., Habeck, A., 2004. Expected changes in water resources availability and water quality with respect to climate change in the Elbe River basin (Germany). Nordic Hydrology 36, 321–333.

Laio, F., Porporato, A., Fernandez-Illescas, C.P., and Rodríguez-Iturbe, I., 2001. Plants in water-controlled ecosystems: active role in hydrologic processes and response to water stress. IV. Discussion of real cases. Adv. Water Resour., 24(7), 745-762.

Ladson, T., 2003. Assessing the Health of Ephemeral Rivers. Review of Geomorphic and Hydrologic Indicators. Land & Water Australia, Braddon, Australia. Avaialable [online]: http://lwa.gov.au/files/products/national-rivers-consortium/pn30272/pn30272.pdf

Lake P.S., 2008. Drought, the “creeping disaster” Effects on aquatic ecosystems. Land & Water Australia. Available [online]: http://lwa.gov.au/files/products/innovation/pn20677/pn20677.pdf

Lake, P.S., 2003. Ecological effects of perturbation by drought in flowing waters. Freshwater biology 48, 1161-1172.

Lake, P.S., Palmer, M.A., Biro, P., Cole, J.J., Covich, A.P., Dahm, C.N., Gibert, J., Goedkoop, W., Martens, K. and Verhoeren, J.T.A., 2000. Global change and freshwater ecosystems: Impacts on linkages between above-sediment and below-sediment biota. BioScience 50: 1099-1107.

Lake, P.S., 2000. Disturbance, patchiness, and diversity in streams. Journal of the North American Benthological Society: Vol. 19, No. 4, pp. 573–592.

Lamouroux N., 2008. Hydraulic geometry of stream reaches and ecological implications. In Gravel Bed Rivers 6: From Process Understanding to the Restoration of Mountain Rivers, edited by H. Habersack, H. Piégay, M. Rinaldi. Developments in Earth Surface Processes, 11, 661-675. Elsevier

Laudon H., 2008. Recovery from episodic acidification delayed by drought and high sea salt deposition. *Hydrology and Earth System Sciences 12*: 363-370

Leadbitter, P., 2007. Managing peatland systems to mitigate carbon release and flooding. Issues 15, December 2007. Looking to the Hills - Newsletter of the Upland Lead Co-ordination Network. Joint Nature Conservancy Council.

Leirs, H., Verhagen, R., Verheyen, W., Mwanjabe, P., and Mbise, T., 1996. Forecasting Rodent Outbreaks in Africa: An Ecological Basis for Mastomys Control in Tanzania. Journal of Applied Ecology, Vol. 33, No. 5 (Oct., 1996), pp. 937-943.

Lioubimtseva E., 2004. Climate change in arid environments: revisiting the past to understand the future. Prog. Phys. Geogr.;28:502–30.

Livingston RJ, Niu X, Lewis FG and Woodsum GC, 1997. Freshwater input to a Gulf estuary: Long-term control of trophic organization. Ecological Applications, vol. 7, pp. 277-299.

Lorenz, C.M., Gilbert, A.J. and Cofino, W.P., 2001. Indicators for Transboundary River Management. Environmental Management 28(1): 115-129.

Lund, J.R., 2006. Drought Storage Allocation Rules for Surface Reservoir Systems. Technical note, Journal of Water Resources Planning and Management, Vol. 132, No. 5, September 1, 2006

Mackay CF, 2001. Cyrus DP. Is freshwater quality adequately defined by physico-chemical components? Results from two drought-affected estuaries on the east coast of South Africa. Mar. Freshw. Res.;52:267–81.

Magalhães M.F, Beja P., Schlosser I.J. & Collares-Pereira M.J., 2007. Effects of multi-year droughts on fish assemblages of seasonally drying Mediterranean streams. Freshwater Biology, doi:10.1111/j.1365-2427.2007.01781.

Magoulick, D.D. and Kobza R.M., 2003. The role of refugia for fishes during drought: a review and synthesis. Freshwater Biology, 48, 1186–1198

Mainka, S., McNeely, J., and Jackson, B., 2005. Depend on Nature: Ecosystem Services Supporting Human Livelihoods. IUCN – The World Conservation Union, gland, Switzerland.

Matthews, W.J. and Marsh-Matthew, E, 2003. Effects of drought on fish across axes of space, time and ecological complexity. *Freshwater Biology 48*, 1232–1253.

Matthews W.J., 1998. *Patterns in Freshwater Fish Ecology.* Chapman and Hall, New York, USA.

McGowan S., Leavitt P.R. and Hall R.I. (2005). A whole-lake experiment to determine the effects of winter droughts on shallow lakes *Ecosystems 8*: 694-708.

MEDA Water, 2007. Drought Management Guidelines. Examples of Application in Mediterranean Countries. Edited by: Iglesias, A., Cancelliere, A., Gabiña, D., López-Francos, A., Moneo,M., and,Rossi, G. Euro-Mediterranean Regional Programme for Local Water Management (MEDA Water). Mediterranean Drought Preparedness and Mitigation Planning (MEDROPLAN). European Commission - EuropeAid Co-operation Office.

Melack, J.M., Dozier, J., Goldman, C.R., Greenland, D., Milner, A.M., Naiman, R.J., 1997. Effects of climate change on inland waters of the pacific coastal mountains and western great basin of North America. Hydrological Processes 11 (8), pp. 971-992.

McDowell, N., Pockman, W.T., Allen, C.D., Breshears, D.D., Cobb, N.; Kolb, T., Plaut, J., Sperry, J., West, A., Williams, D.G., and Yepez, E.A. (2008) Mechanisms of plant survival and mortality during drought: why do some plants survive while others succumb to drought? *New Phytologist 178*(4), 719-739.

Middelkoop, H., Daamen, K., Gellens, D., Grabs, W., Kwadijk, J.C.J., Lang, H., Parmet, B.W.A.H., Scha¨dler, B., Schulla, J., Wilke, 2001. Climatic change impact on hydrological regimes and water resources management in the Rhine basin. Climatic Change 49, 105–128.

Midgley S., 2009. *Strategic Issues for European Wetlands. Priority research proposed by the European Wetlands Network.* IWRM-Net Project Report. SNIFFER, Edinburgh, UK.

Millennium Ecosystem Assessment. (2005). Ecosystems and Human Well-Bring: Wetlands and Water Synthesis. World resources Instittue, Washington, DC.

Mimikou, M.A., Baltas, E., Varanou, E., Pantazis, K., 2000. Regional impacts of climate change on water resources quantity and quality indicators. Journal of Hydrology 234, 95–109.

Monteith, D. T., Stoddard, J. L., Evans, C. D., de Wit, H. A., Forsius, M., Hogasen, T., Wilander, A., Skjelkvale, B. L., Jeffries, D. S., Vuorenmaa, J., Keller, B., Kopacek, J. and Vesely, J., 2007.Dissolved organic carbon trends resulting from changes in atmospheric deposition chemistry. 450(7169): 537-540.

Moore, R.D,. Spittlehouse, D.L. and Story, A., 2005. Riparian microclimate and stream temperature response to forest harvesting: a review. Journal of the American Water Resources Association, 41, 813–834.

Mulholland, P.J., Best, G.R., Coutant, C.C., Hornsberger, G.M., Meyer, J.L., Robinson, P.J., Stenberg, J.R., Turner, R.E., Vera-Herrerra, F., Wetzel, R., 1997. Effects of climate change on freshwater ecosytems of the south-eastern United States and the gulf coast of Mexico. Hydrological Processes 11, 949–970.

Murdoch, P.S., Baron, J.S. and Miller, T.L., 2000. Potential effects of climate change on surface-water quality in North America. Journal of the American Water Resources Association 36, 347–366.

Murray Darling Basin Commission. 2003. Prospects for future deterioration in flow in the Murray Darling Basin.

Naiman R.J., Bunn S.E., Hiwasaki L., McClain M.E., Vörösmarty C.J., and Zalewski M., 2007. The Science of Flow-Ecology Relationships: Clarifying Key Terms and Concepts. Joint White Paper for the ESSP Open Science Conference.

National Drought Policy Commission, 2001. Preparing for Drought in the 21st Century. Report of the National Drought Policy Commission. U.S Department of Agriculture and National Drought Policy Commission. Washington D.C.

Nelson, D.R., Adger, W.N. and Brown, K., 2007. Adaptation to Environmental Change: Contribution of a Resilience Framework. *Annual review of Environment and Resources*, 32, pp 395–419.

Neumann DW, Rajagopalan B and Zagona EA., 2003. Regression model for daily maximum stream temperature. Journal of Environmental Engineering-ASCE 129, 667–674.

New, M., A. Lopez, Dessai, S. and R. Wilby, 2007: Challenges in using probabilistic climate change information for impact assessments: an example from the water sector, Phil. Trans. R. Soc. A. (2007) 365, 2117–2131.

Nicholls, R.J., Hoozemans, F.M.J. and Marchand, M., 1999. Increasing flood risk and wetland losses due to global sea-level rise: regional and global analyses. Global Environmental Change 9, 69-87.

Nowlin W.H., Davies J.-M., Nordin R.N. and Mazumber A., 2004. Effects of water level fluctuation and short-term climatic variation on thermal and stratification regimes of a British Columbia reservoir and lake. *Lake and Reservoir Management 20*: 91-109.

Noy-Meir, I., 1973. Desert ecosystems: environment and producers. Ann. Rev. Ecol. and Systematics, 4, 25-44.

Oba, G., 2001. The effect of multiple droughts on cattle in Obbu, Northern Kenya. *Journal of Arid Environments 49*, 375-386

OECD, 1993. OECD Core Set of Indicators for Environmental Performance Reviews. A Synthesis Report by the Group on the State of the Environment. Environment Monographs No 83. Organisation for Economic Co-operation and Development, Paris.

OECD, 1994. Environmental Indicators. Indicateurs d'environnement. OECD Core Set. Corps central de l'OCDE. Organisation for Economic Cooperation and Development, Paris.

OECD, 1996. Environmental Indicators for Environmental Performance Reviews. Discussion Paper. Group on the State of the Environment. Organisation for Economic Co-operation and Development, Paris.

Olofsson, J., Hickler, T., Sykes, M.T., Araújo, M.B., Baletto, E., Berry, P.M:, Bonelli, S., Cabeza, M., Dubuis, A., Guisan, A., Kühn, I., Kujala, H., Piper, J., Rounsevell, M., Settele, J. and Thuiller, W., 2008. Climate change impacts on European biodiversity – observations and future projections.

Deliverable 1.1. of the Minimisation of and Adaptation to Climate change Impacts on biodiversity (MACIS) Project. http://www.macis-project.net/MACIS-deliverable-1.1.pdf

Palmer, M.A., Reidy-Liermann, C.A., Nilsson, C., Flörke, M., Alcamo, J., Lake, P.S. and Bond, N., 2008. Climate Change and the World's River Basins: Anticipating Management Options. *Frontiers in Ecology and the Environment*, 6, pp: 81–89.

Paoletti, E., Bytnerowicz, A., Andersen, C., Augustaitis, A., Ferretti, M., Grulke, N. Günthardt-Goerg, M.S., Innes, I., Johnson, D., Karnosky, D., Luangjame, J., Matyssek, R., McNulty, S., Müller-Starck, G., Musselman, R. and Percy, K., 2007. Impacts of Air Pollution and Climate Change on Forest Ecosystems — Emerging Research Needs- Proceedings: Impacts of Air Pollution and Climate Change on Forest Ecosystems *TheScientificWorldJOURNAL* 7(S1), 1–8

Parmesan, C., Root, T.L. and Willig, M.R., 2000. Impacts of Extreme Weather and Climate on Terrestrial Biota. *Bulletin of the American Meteorological Society 81*(3), 443-450.

Parry, M.A.J., Flexas, J. and Medrano H., 2005. Prospects for crop production under drought: research priorities and future directions. Annals of Applied Biology 147(3), 211-226.

Pauli, H., Gottfried, M., Reiter, K., Klettner, C., and Grabherr, G., 2007. Signals of range expansions and contractions of vascular plants in the high Alps: observations (1994–2004) at the GLORIA master site Schrankogel, Tyrol, Austria. Global Change Biology, 13, 147–156.

Pauli, H., Gottfried, M., Klettner, C., Laimer, S., and Grabherr, G., 2009. A Global Long-term Observation System for Mountain Biodiversity: Lessons Learned and Upcoming Challenges. International Mountain Biodiversity Conference 2008. International Centre for Integrated Mountain Development, Kathmandu, Nepal.

Pauly D., 1995. Anecdotes and the shifting base-line syndrome of fisheries. Trends Ecol. Evol.;10:430.

Petts G.E., 2009. Instream flow science for sustainable river management. *Journal of the American Water Resources Association (JAWRA)* 45(5): 1071-1086. DOI: 10.1111/j.1752-1688.2009.00360.x

Pfister, L., Kwadijk, J., Musy, A., Bronstert, A., Hoffman, L., 2004. Climate change, land use change and runoff prediction in the Rhine–Meuse basins. River Research and Applications 20, 229– 241.

Phillips, O.L. et al. 2009. Drought Sensitivity of the Amazon Rainforest. Science 323(5919): 1344-1347.

Pires, A. M. and Coelho, M. M., 2000. Benthic macroinvertebrate communities of intermittent streams in the middle reaches of the Guadiana Basin, Hydrobiologia, 435, 167-175.

Planchon, O., Dubreuil, V., Bernard, V. and Blain, S., 2008. Contribution of tree-ring analysis to the study of droughts in northwestern France (XIX–XXth century). Clim. Past Discuss., 4, 249–270.

Poff, N.L.-R., Allan, J.D., Palmer, M.A., Hart, D.D., Richter, B.D., Arthington, A.H., Rogers, K.H., Meyer, J.L., and Stanford, J.A., 2003. River flows and water wars: emerging science for environmental decision making. Frontiers in Ecology and Environment 1(6), 298-306.

Poff NL, Tokar S, Johnson P., 1996. Stream hydrological responses to climate change assessed with an artificial neural network. *Limnology and Oceanography 41*, 857-863.

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E. and Stromberg, J.C., 1997. The natural flow regime. BioScience, 47:769-784.

Poirel, A., Lauters, F. and Desaint, B., 2008. 1977-2006 : Trente années de mesures des températures de l'eau dans le Bassin du Rhône 1977-2006 : Thirty years of water temperature measurements in the Rhône Basin. Hydroécologie Appliquée, 16 (2008), 191-213.

Postel, S., and Richeter, B.D., 2003. River for Life: Managing water for People and Nature. Island Press, Washington, DC.

Pusey, B.J., and Arthington, A.H., 2003. Importance of the riparian zone to the conservation and management of freshwater fish: a review. Marine and Freshwater Research 54, 1-16.

Pyrce, R., 2004. Hydrological Low Flow Indices and their Uses, WSC Report No. 04-2004, pp 37.

Quilbé, R., Rousseau, A.N., Moquet, J.S., Savary, S., Ricard, S., and Garbouj, M.S., 2008. Hydrological responses of a watershed to historical land use evolution and future land use scenarios under climate change conditions, Hydrol. Earth Syst. Sci., 12, 101–110.

Ramsar Convention Secretariat, 2005. Guidelines for the management of groundwater to maintain wetland ecological character. Resolution IX.1 Annex C ii of the 9th Meeting of the Conference of the Parties to the Convention on Wetlands, Kampala, Uganda, 8-15 November 2005 Guidelines. Available [online]:http://www.ramsar.org/pdf/key_guide_groundwater_e.pdf

Rees, G., Marsh, T.J., Roald, L., Demuth, S., Lanen, H.A.J. van & Kašpárek, L, 2004. Hydrological Data, Chapter 4. In: Tallaksen, L.M. & van Lanen, H.A.J. (Eds.) (2004) Hydrological Drought. Processes and Estimation Methods for Streamflow and Groundwater. Developments in Water Science, 48, Elsevier Science B.V., 99-138.

Rees, GN., Watson, G.O., Baldwin, D.S. and Mitchell, A.M., 2006. Variability in sediment microbial communities in a semipermanent stream: impact of drought. Journal of the North American Benthological Society 25(2): 370-378.

Resh, V.H., Brown, A.V., Covich, A.P., Gurtz, M.E., Li, H.W., Minshall, G.W., Reice, S.R., Sheldon, A.L., Wallace, J.B., and Wissmar, R.C. (1988). The role of disturbance in stream ecology. Journal of the North American Benthological Society 7(4), 433-455.

Riservato, E. et al., 2009. The Status and Distribution of Dragonflies of the Mediterranean Basin. Gland, Switzerland and Malaga, Spain: IUCN

Robson B. (2008). *Managing flows for ephemeral streams.* Fact sheet n. 2. Land & Water Australia, Camberra, Australia. Available [online]: http://lwa.gov.au/files/products/environmental-water-allocation/pn20579/ephemeral-streams-final-low-res.pdf

Rodríguez-Iturbe, I., and Porporato, A. (2002). Ecohydrology – a challenging multidisciplinary research perspective. Hydrological Sciences, 47(5), 811-821.

Rodríguez-Iturbe, I. (2000). Ecohydrology: A hydrologic perspective of climate-soil-vegetation dynamics. Water Resources Research, Vol. 36, No. 1, pgs. 3-9.

Rodríguez-Iturbe, I., and Porporato, A. (2005). Ecohydrology of Water-controlled Ecosystems: Soil Moisture and Plant Dynamics.

Rogora, M., Arisci, S., and Mosello, R., 2004. Recent trends of temperature and precipitation in alpine and subalpine areas in North Western Italy, Geografia Fisica e Dinamica Quaternaria, 27, 151–158.

Rogora, M., Arese, C., Balestrini, R., and Marchetto, A., 2008. Climate control on sulphate and nitrate concentrations in alpine streams of Northern Italy along a nitrogen saturation gradient. Hydrol. Earth Syst. Sci., 12, 371–381.

Roshier, D.A., P.H. Whetton, R.J. Allan, and A.I. Robertson, 2001: Distribution and persistence of temporary wetland habitats in arid Australia in relation to climate. Austral Ecology 26, 371-384.

Ruetz C.R., Trexler J.C., Jordan F., Loftus W.R. and Perry S.A. (2005). Population dynamics of wetland fishes: spatio-temporal patterns synchronized by hydrological disturbance. *Journal of Animal Ecology 74*: 322-332.

Ruiz, E., 2008. Management of Natura 2000 habitats. 3170 *Mediterranean temporary ponds. European Communities, Luxembourg. Available [online]: http://ec.europa.eu/environment/nature/natura2000/management/habitats/pdf/3170_Mediterranean_temporary_ponds.pdf

Rump, 1996. State of the Environment Reporting: Source Book of Methods and Approaches. Report from Division of Environment Information and Assessment. United Nations Environment Programme (UNEP/DEIA), Nairobi.

Sadoff, C.W., and Grey, D., 2002. Beyond the River: the benefits of cooperation on international rivers. Water Policy, 4:389-403.

Salagnac, J. L., 2007. Lessons from the 2003 heat wave: a French perspective. Build. Res. Informat., 35, 450–457.

Sedell J.R., Reeves G.H., Hauer F.R., Stanford J.A. and Hawkins C.P., 1990. Role of refugia in recovery from disturbance: modern fragmented and disconnected river systems. *Environmental Management 14*: 711-724.

Shafroth, P.B., Wilcox, A.C., Lytle, D.A., Hickey, J.T., Andersen, D.C., Beauchamp, V.B., Hautzinger, A., McMullne, L.E., and Warner, A., 2010. Ecosystem effects of environmental flows: modelling and experimental floods in a dryland river. Freshwater Biology 55(1): 68-85.

Sheffield J, Wood EF, 2008. Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. Clim. Dyn.;31:79-105.

Schär, C., P.L. Vidale, D. Luthi, C. Frei, C. Haberli, M.A. Liniger and C. Appenzeller, 2004. The role of increasing temperature variability in European summer heatwaves. Nature, 427(6972), 332–336.

Schindler, D.W., 1997. Widespread effects of climatic warming on freshwater ecosystems in North America. Hydrological Processes 11, 225–251.

Schindler, D.W., Bayley, S.E., Parker, B.R., Beaty, K.G., Cruikshank, D.R., Fee, E.J., Schindler, E.U., Stainton, M.P., 1996. The effects of climatic warming on the properties of boreal lakes and streams at the Experimental Lakes Area, northwestern Ontario. Limnology and Oceanography 41, 1004–1017.

Schröter, D., Cramer, W., Leemans, R., Prentice, C. I., Araújo, M. B., Arnell, N. W., Bondeau, A., Bugmann, H., Carter, T. R., Gracia, C. A., de la Vega-Leinert, A. C., Erhard, M., Ewert, F., Glendining, M., House, J. I., Kankaanpää, S., Klein, R. J. T., Lavorel, S., Lindner, M, Metzger, M. J., Meyer, J., Mitchell, T. D., Reginster, I., Rounsevell, M., Sabaté, S., Sitch, S., Smith, B., Smith, J., Smith, P., Sykes, M. T., Thonicke, K., Thuiller, W., Tuck, G., Zaehle, S. and Zierl, B., 2005. 'Ecosystem service supply and vulnerability to global change in Europe'. Science 310, pp. 1 333–1 337.

Senhorst, H.A.J. and Zwolsman, J.J.G., 2005. Climate change and effects on water quality: a first impression. Water Science & Technology Vol 51 No 5 pp 53–59 Q IWA Publishing 2005

Shaw, D.T., 2001. Groundwater development in the Altamaha River watershed: implications for conservation of aquatic ecosystems. Proceedings of the 2001 Georgia Water Resources Conference.

Silvius, M.J., Oneka, M., and Verhagen, A., 2000. Wetlands: Lifeline for people at the edge. *Physics and Chemistry of the Earth Part B – Hydrology Oceans and Atmosphere*. 25:645-652.

Smith, D.M., and Barchiesi, S.B., 2009. Environment as Infrastructure: Resilience to Climate Change Impacts on Water Through Investments in Nature. Perspective Document – Water & Climate Change Adaptation, Adapting to Climate Change in Water Resources and Water Services: Understanding the Impacts of Climate Change, Vulnerability Assessments and Adaptation Measures. World Water Fourm 2009. Istanbul.

Smith,. G. and Darwall, W.R.T. (Compilers), 2006. The Status and Distribution of Freshwater Fish Endemic to the Mediterranean Basin. IUCN, Gland, Switzerland and Cambridge, UK.

Smith JB and Tirpak D. (eds), 1989. The Potential E€ects of Global Climate Change on the United States. USEPA: Washington, DC.

Somville, M. and De Pauw, N., 1982. Influence of temperature and river discharge on water quality of the Western Scheldt estuary. Water Research 16, 1349–1356.

Sprague, L.A. 2005. Drought Effects on Water quality in the South Platte River Basin, Colorado. Journal of the American Water Resources Association (JAWRA) 41(1):11-24.

Stanley E.H., Fisher S.G. and Grimm N.B., 1997. Ecosystem expansion and contraction in streams. *BioScience 7*: 427-435.

Takara K and Kojiri T., 1993. Numerical experiments on effects of global warming on catchment response change. Journal of Hydraulic, Coastal and Environmental Engineering 489: 1±10 (in Japanese with English abstract).

Tallaksen, L.M. and Van Lanen, H.A.J., 2004. Hydrological drought: processes and estimation methods for streamflow and groundwater. Developments in water science 48, Elsevier, Amsterdam, the Netherlands, 579 pages.

Tharme, R.E., 2003. A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. River Research and Applications 19, 397-441.

Thomas, CD, Cameron A, Green, RE, Bakkenes, M. Beaumont, LJ,. Collingham, VC, Erasmus, BFN, Ferreira de Siqueira, M, Grainger, A, Hannah, L, Hughes, L, Huntley, B, van Jaarsveld, AS, Midgley, GF, Miles, L, Ortega-Huerta, MA, Townsend Peterson, A, Phillips, OL, Williams, SE., 2004. Extinction risk from climate change. Nature 427, 145-148.

Tilman, D., and Downing, J.A., 1996. Biodiversity and Stability in Grasslands. In Ecosystem Management: Selected Readings. Eds, Samson, F.B., and Knopf, F.L. Springer-Verlag, New York.

Travade, F. and Carry., L., 2008. Effet de la canicule de 2003 sur les poissons migrateurs en Garonne et Dordogne - Réflexions sur l'effet des rejets thermiques de la centrale nucléaire de Golfech sur la Garonne. Effect of the 2003 heat wave on the migratory fish in the Garonne and Dordogne rivers - Consideration on the effect of the Golfech nuclear power plant thermal discharges in the Garonne river. Hydroécol. Appl., 16: 169-189, DOI: 10.1051/hydro/2009008 (in French).

Trumper, K., Bertzky, M., Dickson, B., van der Heijden, G., Jenkins, M., Manning, P. June, 2009. The Natural Fix? The role of ecosystems in climate mitigation. A UNEP rapid response assessment. United Nations Environment Programme, UNEPWCMC, Cambridge, UK Available [Online]: http://www.unep.org/pdf/BioseqRRA_scr.pdf

UNDP, 2006. Summary Human Development Report. Beyond scarcity: power, poverty and the global water cycle. Palgrave Macmillam, New York.

Valiela I, Geist M, McClelland J, Tomasky G., 2000. Nitrogen loading from watersheds to estuaries: verification of theWaquoit Bay nitrogen loading model. Biogeochemistry;49:277–93.

Van Vliet, M.T.H. and Zwolsman, J.J.G., 2008. Impact of summer droughts on the water quality of the Meuse River. Journal of Hydrology, 353, 1-17.

Várallyay, Gy., 2009. Soil-water stress. Cereal Research Communications 37 (2), pp. 315-319

Vennetier, M.,Borgniet, L., Thabeet, A., Gadbin-Henry, C., Ripert, C., Vila, B., Prevosto, B., Esteve, R., Martin, W., N'diaye, A., 2007. Impact de la canicule 2003 sur les peuplements résineux de la région PACA. Note de synthèse - Impact of 2003 scorching heat on conifers in PACA region (South Eastern France). Synthesis. 14 pp.

Victorian Environment Assessment Council, 2006. River Red Gum Forests Investigation: Discussion Paper Victorian Environment Assessment Council (VEAC), Melbourne.

Vidal, J.-P., Martin, E., Franchistéguy, L., Soubeyroux, J.-M., Baillon, M., Blanchard, M., 2009. Multilevel drought reanalysis over France with Safran-Isba-Modcou hydrometeorological suite. Geophysical Research Abstracts,Vol. 11, EGU2009-7068.

Wagner, I., and Zalewski, M., 2000. Effect of hydrobiological patterns of tributaries on processes in lowland reservoir – consequences for restoration. Ecological Engineering, 16:79-90.

Walther, G.-R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebeef, T.J.C., Fromentine, J.-M., Hoegh-Guldberg, O. & Bairlein, F., 2002. Ecological responses to recent climate change. Nature 416, 388-395.

Water Institute, 2000. Overview of Regional Meteorological Drought Analysis on Western Europe. Technical report, ARIDE project, pp. 104.

Webb, B.W., Hannah, D.M., Dan Moore, R., Brown, L.E., Nobilis, F., 2008. Recent advances in stream and river temperature research. Hydrological Processes, 22, 902–918.

Welcomme R.L., 1986. The effects of the Sahelian drought in the fishery of the central delta of the Niger River. *Aquaculture and Fisheries Management 17*: 147-154.

Whitehead P.G., Wilby R.L., Butterfield D., and Wade A.J., 2005. Impacts of Climate Change on Nitrogen in a Lowland Chalk Stream: An Appraisal of Adaptation Strategies. *Science of The Total Environment 365*: 260-273. Available [online]: http://www.riverkennet.org/content/downloads/KennetAdaptationMeasures29Jul05.pdf

Whitehead, P.G., Wilby, R.L., Batterbee, R.W., Kernan, M., and Wade, A.J., 2009. A review of the potential impacts of climate change on surface water quality. Hydrological Sciences, 54(1): 101-123.

Wilby, R.L., 1994. Exceptional weather in the Midlands, U.K. during 1988-1990 results in the rapid acidification of an upland stream. Environ. Pollut., 86:15-19.

Wilby, R.L. and I. Harris, 2006. A framework for assessing uncertainties in climate change impacts: lowflow scenarios for the River Thames, UK. Water Resources Research, 42 : W02419.1–W02419.10.

Wilby, R.L., P.G. Whitehead, A.J. Wade, D. Butterfield, R.J. Davis & G. Watts, 2006. Integrated modeling of climate change impacts on water resources and quality in a lowland catchment: River Kennet, UK, Journal of Hydrology, 330, 204-220.

Wilhite, D., and Buchanan-Smith, M., 2005. Drought as Hazard: Understanding the Natural and Social Context. In Drought and Water Crises: Science, Technology, and Management Issues. Ed. Wilhite, D. Taylor and Francis, Boca Raton.

Williams D.D., 2006. The Biology of Temporary Waters. Oxford University Press, Oxford, UK.

Wilson, J.B., and Agnew, A.D.Q. (1992). Positive feedback switches in plant communities. Advanced Ecology Research 23, 263–336.

Williams, M.W., Losleben, M., Caine, N., Greenland, D., 1996. Changes in climate and hydrochemical responses in a highelevation catchment in the Rocky Mountains, USA. Limnology and Oceanography 41, 939–946.

Wissinger S.A. and Gallagher L.J., 1999. Beaver pond wetlands in northwestern Pennsylvania: Modes of colonization and succession after drought in D.P. Batzer, R.B. Rader and S.A. Wissinger (eds), *Invertebrates in Freshwater Wetlands of North America: Ecology and Management*, John Wiley and Sons, New York, pp. 333-362.

Witte, J., Meuleman, A.F.M., van der Schaaf, S., and Raterman, B., 2004. Eco-hydrology and biodiversity. In Feddes, R.A.; Rooij, G.H.de; Dam, J.C. van (Eds.) Volume 6: Unsaturated Zone Modelling: Progress, Challenges, and Applications. Wageningen, UR Frontis Series.

WMO. 2008. Manual on Low-Flow Estimation and Prediction. Operational Hydrology Report No.50. WMO-No.1029. World Meteorological Organisation, Geneva, Switzerland.

Wolford, R.A. and Bales, R.C., 1996. Hydrochemical modelling of Emerald Lake watershed, Sierra Nevada, California: Sensitivity of stream chemistry to changes in fluxes and model parameters. Limnology and Oceanography 41, 947–954.

Wood, P.J. and Petts, G.E., 1999. The influence of drought on chalk stream macroinvertebrates. Hydrol. Process., 13, 387-399.

Wright, R.F., and Jenkins, A., 2001 Climate change as a confounding factor in reversibility of acidification: RAIN and CLIMEX projects. Hydrol. Earth system Sci., 5:477-486.

Wrona, F.J., Prowse. T.D., Reist, J.D., Hobbie, J.E., Lévesque, L.M.J., Vincent, W.F., 2007. Climate Change Effects on Aquatic Biota, Ecosystem Structure and Function. *AMBIO: A* Journal of the Human Environment *35*(7), 359-369.

WWF France. 2004. Les Impacts du Changement Climatique su la Biodiversité en France (métropolitaine et Outre-mer), Synthèse et Priorités d'actions pour le WWF France.

WWF. 2005. PowerSwitch! Campaign, Europe feels the heat – the power sector and the extreme weather.

Zaidman, M.D., Ress, H.G. and Young, A.R., 2002. Spatio-temporal development of streamflow droughts in northwest Europe. Hydrology and Earth System Science. 6: 733-751.

Zalewski, M., 2006. Ecohydrology – an interdisciplinary tool for integrated protection and management of water bodies. Arch. Hydrobiol. Suppl. 158/4 (Large Rivers 16/4), 612-622.

Zalewski, M., 2000. Guest Editorial. Ecohydrology – the scientific background to use ecosystem properties as management tools towards sustainability of water resources. Ecological Engineering,, 165:1-8.

Zebisch, M., T. Grothmann, D. Schroeter, C. Hasse, U. Fritsch and W. Cramer, 2005. Climate Change in Germany: Vulnerability and Adaptation of Climate Sensitive Sectors. Federal Environmental Agency (Umweltbundesamt), Dessau, 205 pp.

Zöckler, C. and Lysenko, I., 2000. Water Birds on the Edge: First circumpolar assessment of climate change impact on Arctic breeding water birds. World Conservation Monitoring Centre, Cambridge, UK. 23 pp.

Zwolsman J.J.G., van Bokhoven A.J., 2007. Impact of summer droughts on water quality of the Rhine River - a preview of climate change?, Water Science & Technology, Vol 56, No 4, pp 45–55

7. Annex

7.1. Impact Matrix

Drought 'mechanism' or cause of drought (but then drought can contribute to higher temperatures, etc, etc – feedback loop problem)	Direct Impacts on Environment	Indirect Impacts (1)	Indirect Impacts (2)
Reduced precipitation	• Reduced volumes of water available in rivers and streams • Break in water connectivity (between main waters and back waters, streams and rivers, wetlands and surface and groundwater) • Reduced volumes of water in lakes and other standing water bodies • Reduction in water conveyance (movement of water between lakes, pools, reservoirs, etc, and nutrient flows) • Reduction in groundwater recharge from surface waters	• *Reduction in navigable waters (commercial and recreational)* • Reduced volumes available for water supply (increasing concentrations of effluent pathogens) • Possible reduced volumes of freshwater available for wastewater treatment • Possible reduced volumes of freshwater available for industrial water treatment processes (affecting clearance capacity of treatment plants) • Riparian vegetation die back and reduced habitat area and vegetation shading • Vegetation physiological stress (increased leaf abscission, both decrease and increase in seed production) • *Reduced ability to generate electricity from HEP (due to low flows, multiple use priorities of reservoirs, and need to maintain downstream environmental flows and other*	• Increase in particulate and organic matter in water courses and bodies (due to reduced volume of water and therefore higher concentrations of matter, and possible increase in plant abscission) • Possible alteration of animal food resources (due to lack of vegetation and effects on food chain) • Possible increase in rodent infestations and human contact (hanta-virus infections, infections from rodents as carriers of fleas and ticks) • Possible increase in human/wild animal interactions (animal mortality) • General natural habitat loss • Increasing opportunity for non-native invasive species to establish (increase in niche availability and reducing biodiversity and niche prey species) • Reduction in no. of filter feeding organisms (and larvae) as flowing water becomes standing water (reduction in biodiversity) • Reduction in numbers and possible eventual loss of resident biota in lakes and wetlands • Higher chemical loading and water temperatures combined may increase primary productivity in freshwater, leading to increased dissolved oxygen during day and reduced dissolved oxygen at night • Pollutant concentration combined with higher water temperatures more likely to be out of range tolerated by freshwater organisms • Reduction in timber production/harvest and certain agricultural trees suffer from lack of water and reduce yield (e.g. olives) • Increased energy and chemical costs for drinking water treatment

		uses)
		• Land subsidence and other geomorphological changes (due to falling groundwater)
		• Soil structural changes - breakdown of topsoil into small particles (due to drying of organic matter, exacerbated by dying plants reducing shading of the soil surface)
		• Soil capping (causing excessive run-off when rains return and poor infiltration)
		• Reduction in dilution function of water courses and bodies for pollutants
		• Reduced water quality in surface water courses and water bodies (changes in pH)**
		• Saline intrusion in coastal aquifers (due to reduced recharge and/or increased abstraction)
		• *Damage to infrastructure (due to increased sediment, landslides?) and change required in infrastructure operations*
			• Salts and suspended solid concentrations increase in water
			• Dissolved oxygen decreases in water
			• Bed sediments of water bodies (esp. lakes) may release phosphorus and nitrogen, increasing algal growth (toxic blue-green algae blooms)
			• Increased fish predation (due to concentration of fish in standing water bodies)
			• Possible increase in parasitism and disease (esp. fish) due to higher densities of freshwater biota in standing waters
			• Migration and concentration of species
			• Reduction in shelterbelts and habitat corridors (due to fires and/or drying)
			• Decrease in animal breeding and increase in mortality (impacts on wildlife and domesticated agricultural animals)
			• *Higher costs of supplemental water*
			• *Reduced milk production*
			• *Increase in future dam construction????*
			• Effects on anadromous fish migration patterns
			• *Possible archaeological and cultural damage*
			• *Reduced fire fighting capability*
			• *Public safety risk (increased morbidity)*
			• *Possible increase or change in existing patterns of mosquito-borne diseases (West Nile fever, Chikungunya fever)*
			• *Possible increase or change in existing patterns of sandfly borne disease (leichmaniasis)*
			• *Possible increase in campylobacter in chickens*
			• *Possible increase or change in existing patterns of tick borne diseases (transmitted through birds and agricultural animals)*
			• *Migration of people (changing population densities)*
			• Possible impact on estuarine and marine water quality
			• Change between carbon sequestration to carbon sources (fires, reduced forest productivity, etc)
			• Impacts on alpine habitats (ACQWA):
			    ○ Reduction in permafrost
			    ○ Increase in slope instability (landslide)
			    ○ Possible increased sedimentation of downstream rivers and watercourses

			• Peatland drying, habitat loss, turning carbons sink into source, increase of fire risk (spontaneous combustion) • Chloride toxicity in plants, excessive leaf abscission, plant death, reduced yield in agricultural crops • Landscape diversity/quality reduced – visual and recreational impact and use • Bird breeding and migration changes (due to changes in quality and quantity of wetlands and water courses and bodies
Increasing air temperature	• Higher water temperatures in water courses and bodies (consequence of lower flows and possible higher temperatures)*	• Soil structural changes - breakdown of topsoil into small particles (due to drying of organic matter, exacerbated by dying plants reducing shading of the soil surface) • Soil capping (causing excessive run-off when rains return and poor infiltration) • Possible stratification of water in lakes and water bodies	• Reduction in soil organic matter • Flash flooding due to soil instability and landslides (mud slides in alpine areas) and higher surface run-off due to poor infiltration into soils • Increased coastal erosion and habitat change • Water course changes due to weakened river banks and altered flow patterns • Possible impact on fresh, estuarine and marine water qualities (increase in algal blooms, and possibly human health) • Power station cooling water discharge temperatures may exceed permitted temperatures into water courses with less water and higher temperatures than normal
Increase in wind speed and frequency	• Forest and bush/scrub vegetation fires* • Dust storms (possibly containing ash and soot from fires)*	• Reduced air quality (possible increase in aeroallergens) • Dust and ash can travel 1000's miles by wind – transboundary and continental effects on land and water bodies (including the marine habitat) • Increased soil erosion	• Run-off from burnt areas toxic • Landscape diversity reduced – visual and recreational impact and use • *Impact on human health* • Forest and bush/scrub fires can cause other fires due to aerial transport of embers • *Damage to infrastructure (by fires and dust storms)*

Notes:
* this is not always an effect of drought and may/may not occur. Equally, a drought can contribute to this effect.
** this could be a direct impact, but the first impact will be reduced water volume, before water quality deteriorates?

Drought frequency affects biota in different ways – recovery and resilience rates different for many organisms and habitats.

7.2. Potential key research questions

Summary of research questions which international experts (feedback from the Xerochore Workshop II) were expecting to see addressed. These questions are mainly concerned with how environmental impacts of drought are currently and can be dealt with in the context of the WFD, many of which remain unanswered at present.

7.2.1. Research questions from a science perspective

- Can problems be put into a hierarchy along with data available and what is needed to develop an idea of ecosystem sensitivity to drought?
- Not all ecosystems are equal - due to morphology and hydrology – for example in terms of groundwater and surface water links, and, therfore, should not be studied as such.
- A definition of ecosystem sensitivity may be useful
- Early warning - when do we know a drought is affecting biology, for example through changes in water temperature, dissolved oxygen, etc.?
- Do we have models to add in the complexity in a dynamic way – to allow us to react – is there a risk methodology – can it work here – can we develop a better probabilistic way to think? (which goes against the concept of stationarity and increasing accuracy in probability approaches requires a move away from hydraulic history – and this does not fit with the reinforcing comments in the final plenary of the need to improve probability forecasting).
- Can you let forests and ecosystems manage themselves – should we be reducing forest size and thickness during or before drought to reduce water use and increase streamflow/recharge – or where rainfall is lower? What impact will this have on C02?
- Ecosystems have always worked with drought – are we going to pocket loss and maintain normal flows, or should the river suffer during drought too?
- What restorative means are possible and necessary? What can we design to develop buffering capacity for: headwater systems, riparian areas, land and water ecosystems, groundwater and surface water connectivity?
- Agriculture should be recognised as part of the natural system – we have to make choices about what to save/preserve in the future – (landscape management is also important)
- How to get the river basin management data – as a scientific community to work with? Often river basin management data is for management purposes, and therefore limited in terms of what is collected, or it is too detailed. What is needed is an understanding of the impacts on macro fauna, and to better understand did the drought affect all watercourses/bodies, and if not, why not? Tools are required for managers of water to understand and investigate this.
- Is desalination realistically a technology to increase water as part of a response strategy to drought, in extreme cases, and should this be used to support environmental water benefits?
- We need to understand better the role refugia plays and how this needs to be linked to different types of landscape we want to save/protect.
- Environmental flows, perhaps more stress not just on minimum flows, but on the need for ecohydrographs and variable flows? This is especially important for agriculture. What is the relationship between dynamic water abstraction from rivers for agriculture and the environment?
- Agriculture – is an environmental service and should be considered so. Soils filter and clean water, land is managed to improve it in some ways, (not all), should we say something on using Integrated Pest Management to offset drought impacts such as an increase in insects?

7.2.2. Research questions from a policy perspective

- Habitat and habitat management. Is it possible to transfer flow management practices from the WFD and hydrology into habitat management (eco-hydraulics and environmental flows)?
- Are biological indicators in the WFD useful to monitor drought – do they react to extreme events?
- The 27 Member States have different interpretations of WFD Art.14 and ways of doing this – there are degrees of stakeholder involvement. At the small scale, some good examples in Europe and worldwide, for example local people becoming connected with their wetland – keeping an eye on it, reporting change, helping manage it – this approach is strong in the USA.
- Research needs to 'link' with landscape stakeholders -. To protect the wider landscape against pressures, especially during drought.
- Water companies or national utilities are the main extractors of water in predominantly rain fed parts of Europe, therefore they have strategic and tactical measures to deal with droughts. These should be incorporated into RBMP's. Should utilities be involved in the dilaogue? Most the water providers work is on impacts on quality, not quantity, and drought hits both.
- The Groundwater Directive focuses on the avoidance of particular pollutants/substances, from entering the groundwater and to avoid over-extraction to allow recharge. Drought is mentioned with respect to those interventions in surface waters for the purposes, amongst others, of mitigating the effects of droughts. The inputs of pollutants into groundwater that result from these interventions are exempted from the measures otherwise provided for by the Directive..
- Research questions: policy documents assume everything is linear and after drought the assumption is that everything will go back to normal from a hydrological and management perspective, but actually things are gone, the soil for example, and this is not always due to poor farmer management of the soil.

7.3. Acronyms

COD Chemical Oxygen Demand

DOC Dissolved Organic Carbon

EEA European Environment Agency

GES Good Ecological Status

IBA Important Bird Areas

IPCC Intergovernmental Panel on Climate Change

IWRM Integrated Water Resources Management

POM Particulate Organic Matter

RBMP River Basin Management Plan

SAC Special Areas of Conservation

UNDP United Nations Development Programme

WFD Water Framework Directive

7.4. Glossary

Abiotic, pertaining to the non-living part of an ecosystem or to an environment where life is absent.

Abstraction, removal of water from any source, either permanently or temporarily.

Biomass, total mass of living material in a given body of water.

Climate change, significant change observed in the climate of a region between two reference periods.

Climatic region, region in which there is a relatively uniform climate, according to specific criteria.

DPSIR, the causal framework for describing the interactions between society and the environment adopted by the European Environment Agency: driving forces, pressures, states, impacts, responses (extension of the PSR model developed by OECD). Terminology source: http://glossary.eea.europa.eu

Drought, a sustained and regionally extensive occurrence of below average natural water availability due to climate variability. Relative to normal conditions.

Dry year, year during which precipitation or stream flow is significantly less than usual.

Ecosystem, System in which, by the interaction between the different organisms present and their environment, there is a cyclic interchange of materials and energy.

Environmental flow, the water regime provided within a river, wetland or coastal zone to maintain ecosystems and their benefits. Other definitions and terms regarding environmental flows exist and include minimum-, in stream- and ecological flow. However, the above definitions and the term 'environmental flow' are the only ones truly encompassing the holistic nature of the concept. The updated definition reads 'Environmental Flows describes the quantity, quality and timing of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems'.

Water consumption, is the portion of the withdrawals (water supplied) that is not returned to the environment after use, it is either consumed by activities or discharged into the sea or evaporated. **Shortage**, the relative shortage of water in a water supply system that may lead to restrictions on consumption. Shortage is the extent to which demand exceeds the available resources and can be caused either by drought or by human actions such as population growth, water misuse and inequitable access to water.

Water deficit, cumulative difference between potential evapotranspiration and precipitation during a certain period in which the precipitation is the smaller of the two.

Water demand, actual quantity of water required for various needs over a given period as conditioned by economic, social and other factors.

Water loss, in a water balance: sum of water lost from a given land area during any specific time by transpiration from vegetation (agricultural crops or native vegetation) and building of plant tissue, by evaporation from water surfaces, soil moisture and snow, and by interception.

Water management, planned development, distribution and use of water resources.

Water policy, collection of legislation, legal interpretations, governmental decisions, agency rules and regulations, and cultural responses which guide a country's actions concerning the quantity and quality of water.

Water quality, physical, chemical, biological and organoleptic properties of water.

Water scarcity, a situation where there is insufficient water to satisfy normal water requirements.

7.5. List of contributors

Name	Organization	Country
Christodoulos, Artemis	Private Consultant and Formerly Water Development Department	Cyprus
Dionysis, Assimacopoulos	National Technical University of Athens	Greece
Stefano Barchiesi	International Union for Conservation of Nature (IUCN),	Switzerland
Bernard Barraqué	ENGREF AgroParisTech, France	France
Melanie Bauer	Water Management Center, Bauer & Olsson GbR	Germany
Gabriele Bonaiti	Drainage and Irrigation District "Riviera Berica" - in behalf of Euro-Mediterranean Irrigators Community	Italy
Mohamed Boufaroua	Soil and Water Conservation Directorate	Tunisia
Abdullah Ceylan	Turkish State Meteorological Service	Turkey
Francis Chiew	CSIRO Land and Water	Australia
Jan Cools	Soresma BU WATER	Belgium
James Dalton	International Union for Conservation of Nature (IUCN)	Switzerland
Abdelkader El Garouani	Faculty of Sciences and Techniques– Fez	Morocco
Jochen Froebrich	ALTERRA Wageningen	The Netherlands
Carlo Giupponi	Fondazione Eni Enrico Mattei	Italy
Peter Kristensen,	European Environment Agency (EEA)	Denmark
Gareth James Lloyd	UNEP-DHI Centre	Denmark
Carlos Machado	Universidade Atlântica	Portugal
Rodrigo Maia	Faculty of Engineering, University of Porto (FEUP)	Portugal
Paola Minoia	University of Helsinki, Department of Geography	Finland
Nikolaos P. Nikolaidis	Technical University of Crete	Greece
Oldřich Novicky	Masaryk Water Research Institute	Czech Republic
Gunnar Nützmann	Leibniz-Institute of Freshwater Ecology and Inland Fisheries (IGB), Dept. Ecohydrology and Professor of Hydrology, Humboldt-University Berlin, Geographical Institute	Germany
Jørgen Eivind Olesen	Aarhus University, Dept. of Agrocology and Environment	Denmark
Charis Omorphos	Water Development Department (WDD) of the Ministry of Agriculture, Natural Resources and Enivronment of the Government of the Republic of Cyprus	Cyprus
Manuel Pulido-Velásquez	Hydraulic and Environmental Engineering Department, Technical University of Valencia	Spain

Maria Helena Ramos	CEMAGREF	France
Simone Rossi	Institute for Environment and Sustainability, Joint Research Centre (JRC)	Italy
Tania Runge	COPA-COGECA	Belgium
Amir Sadoddin	Gorgan University of Agricultural Sciences & Natural Resources	Iran
Jose D Salas	Colorado State University	USA
Eric Sauquet	CEMAGREF	France
Aart Schrevel	Wageningen University and Research Centre (WUR),	The Netherlands
Yves Souchon	CEMAGREF	France
Henny van Lanen	Wageningen University and Research Centre (WUR)	The Netherlands
Steven Wade	HR Wallingford	UK
Mike Walker	Department for Environment, Food and Rural Affairs (DEFRA)	UK