WHITE PAPER

Water Science Alliance

PRIORITY RESEARCH FIELDS

HELMHOLTZ
CENTRE FOR
ENVIRONMENTAL
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Water Science Alliance

White Paper

Priority Research Fields

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Contents

Preamble: Scope of the White Paper

This document presents six research fields, which have been identified and developed by a range of representatives of the German water research community as the priority research fields which mirror the Grand Challenges facing the water science community today.

The White Paper is presented to the funding agencies and decision makers in science politics as a statement from the science community on the research fields to be prioritized in the coming years. Describing the current research needs in water science, it draws the general lines to be followed in interdisciplinary water research, and shall serve as orientation when establishing new research programs and funding calls.

The White Paper emphasizes the urgent need for integration in water research, in order to enable water scientists to develop adequate solutions to the complex problems emerging from increasing dynamics in the environment. Therefore, the goal is to bring together existent research competences within Germany, to strengthen the national water research community, to create synergy among the different disciplines, and to join forces with the international water research community in a strong and visible partnership.

Joint research initiatives developing along the ideas presented in the White Paper are also to form the foundations for promoting integrated hydrological sciences through training and education of young researchers.

Introduction

The Scientific Community in Germany shows a wide range of competences in the field of water research, including the assessment of water quality and quantity, the development of innovative products in water technology, observation, hydrological modelling and early-warning systems, as well as a broad experience in water management.

However, in view of the pressing water problems worldwide and an increased need in practical solutions to concerns arising from global and climate change, we need to reconsider how science can contribute to take on the emerging issues related to water as a resource. The key questions are: 1) what are the related scientific challenges that need to be addressed in the future? And 2) is the water research community in Germany adequately positioned and structured to meet the grand societal challenges of today and the future?

Water Research in Germany

Water research competences in Germany are distributed among a wide range of institutions with focus on various disciplines. There are approximately 500 institutes conducting water or water-related research in more than 100 institutions (see Figure 1). Disciplines range from hydrology in a broad sense (including hydrogeology, pedology, water-chemistry, hydro-meteorology, coastal zone hydrology etc.), ecology (including aquatic ecology and ecotoxicology, limnology etc.), water engineering (urban water management, water technology, hydraulics, regional planning), numerical modelling, monitoring, data management through to socio-economics, law, water ethics and water management (IWRM).

One reason for this fragmented research structure is the heterogeneous funding system: universities are funded by the federal states ("Länder"), non-university research institutions as well as the Helmholtz National Labs are funded by a mix coming from 1) the national ministries and 2) the federal states. The basic funding is complemented by a complex system of project funding, which rarely follows a long-term perspective and usually lacks general coordination to integrate results between different

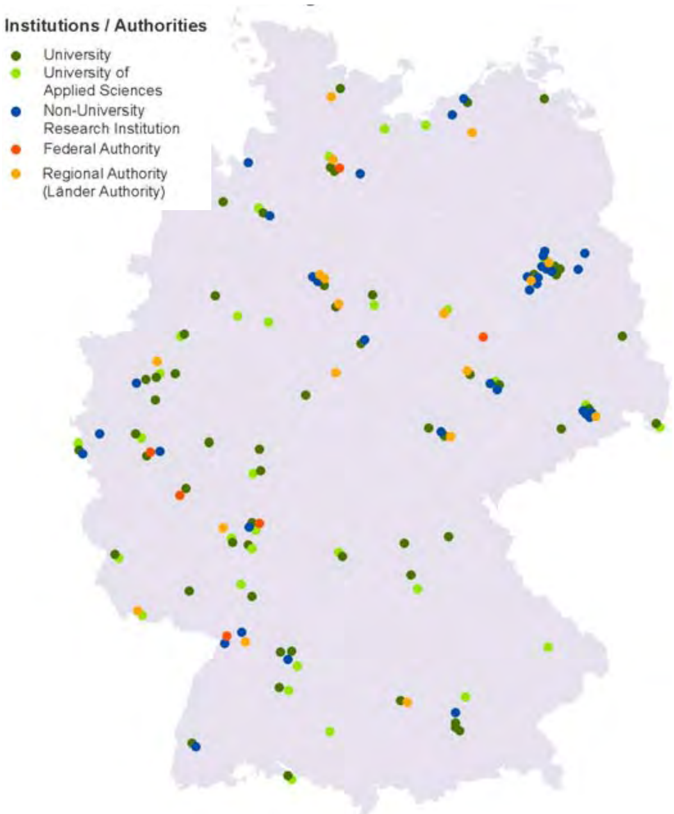

Figure 1: Institutions conducting water or water-related research in Germany

projects or research groups. As a result of this, research approaches commonly applied are often focused only on one specific sector which is covered by the institute receiving funding. Consequently, the problem perspective adopted, the methodological and technological approaches employed and the solutions offered are limited. In general, a single group or institution lacks the ability to analyse, evaluate and optimise complex water-related problems as a whole. Various collaborative research activities were therefore initiated and have shown good short-term results. However, they did not lead to stable cooperation networks, due to the temporary character of the funding. In Germany, this issue has been addressed for some years by the German Research Foundation (DFG). In a compendium of their analyses of the German water research community, the Senate Commission on Water of the DFG (DFG-KOWA) concluded already in 2003 that the water research community in Germany is well developed in terms of the individual expertise but extremely dispersed and not adequately structured to meet the challenges of the future as one of the global research leaders in the field of water.

An empirical analysis on the current status of water research competences within the German scientific community is currently being conducted by the Helmholtz Centre for Environmental Research, funded by the Federal Ministry for Education and Research (BMBF). Results will be available at www.watersciencealliance.org/online-portal from January 2011.

The Water Science Alliance

Against the described background, the Helmholtz Centre for Environmental Research – UFZ, which is the German National Laboratory for Environmental Research, has started in 2009 to develop a concept called the “Water Science Alliance” under the mandate of the senate of the Helmholtz Association. The Water Science Alliance aims at joining and strengthening the existing competences in water research in Germany and creating a long-term, reliable framework for work on some of the complex issues of water science. At the core of this concept lies the conviction that a reliable bundling of competences with conceivable output can only be achieved within a Water Science Alliance, if the respective partners develop a common research strategy to address some of the most relevant challenges. The Water Science Alliance will be the tool to bring together leading groups and institutions in Germany and strategically interlink them in a complementary way in so-called “Thematic Clusters”. The Thematic Clusters will be clusters of competences fostering basic as well as applied research for the conceptualisation and development of concrete solutions to pressing water problems, both nationally and globally. Therefore, the clusters will not only include research institutions such as universities and national labs, but also partners from the Federal Agencies and the industry.

The funding for the Water Science Alliance will be specifically used to finance only those research efforts that build a bridge and create synthesis between different research competences in different research groups. This will enable the water research community to produce more visible results also on the international level. The Water Science Alliance will bring added value to the research fields through synergy and additional findings by integrating different disciplines. The Thematic Clusters are to be established in order to conduct research on the prioritized Research Fields discussed later in this document. Through a coordinated effort and by linking the Thematic Clusters the Water Science Alliance will strengthen the Water Research Community through common methods (e.g. common modelling tools), common field sites, aligned data management and monitoring, sharing of competences in social sciences, and the development of common concepts for implementation (water management), as well as common outreach activities and common graduate schools.

A particular target of the Water Science Alliance is the promotion of young scientists and study programs that foster the abilities of the coming generation of water scientists. Such programmes shall enable young scientists to understand and deal with the highly complex and interacting environmental and human systems that are relevant for water as a resource, and to develop and use the tools and opportunities of this and future generations. A key to this, among others, is the interaction with internationally leading research groups. The Water Science Alliance therefore develops strategic cooperations with leading institutes in Europe and overseas, and invites leading international scientists to contribute to mutually beneficial synthesis projects.

For more information on the Water Science Alliance see www.watersciencealliance.org.

Prioritizing Research Fields

In order to identify the grand challenges in water a preparatory committee was formed in December 2009 comprising scientists from a wide range of research institutions, learned societies, representatives from the Federal Ministry for Education and Research (BMBF), the Federal Ministry for the Environment, Nuclear Safety and Nature Conservation (BMU), the German Research Foundation (DFG) and the Federal Agencies with responsibilities in the water field. In the course of several meetings of this committee, the need for a joint effort of the water science community along the lines of common research questions was confirmed. Initial ideas for such grand challenges were brought forward and elaborated among the members of the committee and additional experts from the respective fields. The result of this preparatory work was a first draft of the White Paper which contained what the group considered to be major issues exhibiting national and international importance to be examined with priority.

The 1st Water Research Horizon Conference on “New Initiatives in Water Research 2010” which took place on 13th and 14th of July 2010 in Berlin served as a forum for the water community to discuss the proposed research fields in the White Paper and to identify missing aspects. More than 200 participants from all fields of the German water research community as well as a group of leading international experts participated in the discussions and contributed with their ideas to the further revision of the White Paper. After the conference the White Paper was made publicly available and was open for contributions from the water community. It then was revised and complemented with the impulses given. The result of this combined effort is the White Paper presented below.

This White Paper presenting 6 priority research fields addresses the funding agencies as well as the water community in general. It puts forward what the water research community regards as those fields of research that are most pressing and need a joint, interdisciplinary effort in order to be resolved. It is presented to the Federal Ministry of Education and Research (BMBF), the Federal Ministry of the Environment, Nuclear Safety and Nature Conservation (BMU) and the German Research Foundation (DFG) as a statement from the Science Community. The White

Paper will be used to subsequently formulate detailed research programs in the various research fields. Additionally, they are also submitted as themes for the 8th Framework Programme of the EU and other European / international funding programmes.

Call for Scientific Coordination

A key to the successful integration of the competences available at different research organizations and in the various water-related disciplines is scientific management. Adequate research management requires careful and well-structured coordination of research efforts and a skilled handling of a process that integrates the knowledge from the different fields to the degree necessary for promoting successful, visible, and sustainable results. Research management goes far beyond general and administrative management and needs to be acknowledged as a necessary tool for successfully integrating water research efforts, which cannot be done as a sideline by one or several researchers involved in the project. Each Thematic Cluster of the Water Science Alliance will require a minimum of an administrative and a scientific manager. The latter is to handle the scientific coordination of the respective field of research.

Structure of the White Paper

The 6 Research Fields presented in this White Paper are different in their structure and specification. Even though presented separately, they are all interlinked and some aspects within the Research Fields can always be considered as cross-cutting topics. The complex nature of water related problems and the role of water in almost all sub-systems and processes of our environment offers numerous ways of structuring the White Paper.

As an overall goal we see the development of a sound scientific base for the “integrated management of landscapes and resources” as a response to the complex nature of the water system and to Global and Climate Change”.

The six Research Fields can be grouped into 3 categories as follows:

A) Generic water problems of global dimension

1. “Challenges Emerging from Global and Climate Change: Food and Water, Mega-Urbanisation, Risk and Vulnerability”
2. “Managing Water Beyond IWRM: Target Setting, Instrument Choice and Governance”

B) Strengthening methodological key competences

3. “Understanding Matter Fluxes at the Catchment Scale – Safeguarding Our Health and the Environment”
4. “New Approaches to Observation, Exploration and Data Assimilation in Water Research”
5. “A Community Effort Towards Model Development and Data Integration for Water Science”

C) Complex water management in a priority region

6. “Water Scarcity: New Perspectives for a Circum-Mediterranean Research Case”

In proposing a specific region in Research Field 6 we aim to bundle the ongoing and planned activities in order to produce visible results for a region of significant relevance for Europe as a whole and demonstrate the applicability of the conducted research (see description of RF 6).

It should be noted that this White Paper is not a research programme but rather a description of the priority research fields. The White Paper should serve as a basis for detailed research programs which shall be developed by the German and international water science community.

Research Field 1

New Challenges Emerging from Global and Climate Change: Food and Water, Mega-Urbanisation, Risk and Vulnerability

Global Change is a complex phenomenon that is driven by many interacting factors: Population change and technological advances lead to an increased economic activity, global trade and human welfare. Land use change has a major impact on soil and water resources as well as biodiversity. The growing use of the earth's natural resources creates significant challenges but also opportunities to our society. The primary socio-economic consequences can be seen in growing urban agglomerations, an increasing division of labor and a globalization of markets. The globalization of economic activities has enabled many economies to increasingly rely on imported natural resources instead of their own endowments. However, the closer integration of economic activities around the globe has also led to an overuse of environmental resources. These trends and developments have severe impacts on water availability and water use in many regions of the world. Climate change will amplify these impacts, and human capacity to cope with the adverse affects may be exceeded. Consequently, the vulnerability of the population in many parts of the world will increase. In the proposed research field "New Challenges Emerging from Global and Climate Change" the focus lies on four major topics:

Water for Food, Blue and Green Water, Virtual Water

With an expected increase of the world's population to roughly 9 billion by 2050, the global food production will have to increase by at least 70 percent in order to keep up with increasing food demand and the change in diets of large parts of the world's population. Water will be one of the major constraints to achieve this. Even today, in many cases food is produced with a non-sustainable rate of water use due to an unsustainable management of water consumption. Inefficient irrigation systems are the rule, despite the availability of appropriate technologies and strategies, leading to an over-exploitation of surface and ground waters and a degradation of soils. These trends will accelerate in many regions of the world, not least due to climate change. At the same time, additional demand for water and land may come from an increased demand for bioenergy, most notably through the support policies of many governments for increasing the production of biofuels. Is the increased competition for land leading to a competition for water and is this significant in the future? Is the more pronounced role of international trade in the food market amplifying these trends?

While various global water food analyses have been initiated and conducted over the last decade, there is a lack of understanding about the global and regional impacts of these developments. A broad range of disciplines like hydrology, ecology, economics, agro-science, social science, and others need to be taken into account in order to fully understand the links between human action and the natural environment. In particular, research on the impact of the global drivers of water demand on the local water resources and their impact on economic well-being is still a challenge. The inclusion of the concepts of green water (water stored in and moving through plants and soils as a major factor for the ability of crops to grow) and virtual water (water that is so to speak embedded in products during their production process) can contribute to an improved understanding of the underlying water flows and water allocation mechanisms, thus leading to a better identification of drivers and impacts of water-related changes. The different physical properties and ecological relevance of blue water (water stored in lakes, rivers and groundwater bodies) and green water have not yet been taken into account in economic analysis. There is a need of concepts on accounting for green, blue and virtual water. Gaps on the analytical side need to be identified. The application of these concepts will highlight the inefficiency in many forms of water use and help identify distortions in the allocation mechanisms for water in current water markets.

The process of globalization in economic activities has not only resulted in a strong increase in international trade, it has also made it possible for countries to import products which require natural resources such as water, which are not in ample supply locally. The trade in virtual water constitutes an important component of the international division of labor. Unfortunately, the inefficient or often inexistent pricing or charges of water distort the incentives for developing water intensive activities in locations where water is most abundant and importing goods as virtual water where it is most scarce. Instead, water scarce countries often export water intensive goods at the expense of overusing their own resources. Instruments and institutions that govern a rational use of water are necessary to allow a beneficial trade of virtual water. Targeted green water management is required to improve water productivity in agriculture and to allow for sustainable water management with a focus on agricultural water use and ecosystem conservation.

Some key research questions in this field are:

- Do we have the tools to integrate the relevant disciplines, such as hydrology, ecology, economics, agro-science, social science, in order to fully understand the impacts of global change on the water resources at the global, regional and local scale?
- What kind of economic analyses need to be developed in order to grasp the different types of water („blue" and "green") and how can they be linked to the value of virtual water, in particular with respect to their value in water scarcity?
- What are the opportunities and limits of reflecting virtual water use in the international trade system for better water governance?
- What new technologies may be used to increase agricultural productivity while minimizing land-surface and water used?
- How can water use efficiency be achieved and what are the respective management tools that help control water dissipation and promote water reuse at a global scale?
- What are the environmental water needs to sustain biodiversity, ecosystem processes and ecosystem services?
- How does an adequate "transition management" look like, to go from current water management to a sustainable water management that considers all scales: local management challenges (knowledge, technologies), regional (rights, markets), global (trade rules)?
- How can "good governance" in water allocation and virtual water trade be achieved without disadvantaging the poor? What institutions and instruments can provide the respective incentives?

- What are the alternatives to current water allocation rules (institutions, property rights, prices) for an efficient allocation of water?

Megacities, water and urban metabolism

Urban change, with mega-urbanization being the most visible trend of the 21st century will affect water flows within cities and between cities and their hinterland. A rapidly increasing number of megacities is *the* phenomenon of the 21st century. While the number of cities with more than ten million inhabitants was three in 1950 and is currently around 20, it is expected to increase to more than 60 by 2050. The dependence of these agglomerations on water as well as the production of tremendous volumes of wastewater does not only affect the cities themselves, but also their surrounding areas. Water supply and waste water treatment are among the decisive factors determining the further development and functioning of megacities. Medium-scale cities (500.000 – 5 million inhabitants) may experience the same problems with similar growth rates – thus, the term “mega” in this case may refer to the size of the city, to the rate of change, or to the characteristic problems associated with growth rates typical for the fast growing cities of emerging countries. The current situation is mostly characterized by poor sanitation leading to health risks, insufficient infrastructure, unsustainable waste management, uncontrolled “informal” settlements, and an over-exploitation of surface and ground waters, putting the reliability of water supply at risk. In-migration from the rural surroundings of the cities and over-exploitation of water, food and other resources in the vicinity of these cities may lead to regional water crises and water scarcity. Because a majority of megacities is located by or near the coast, where they are subject to changes in sea-level and an increase in extreme weather conditions, coast-city interactions are of particular relevance in this context. The challenges for future water management are therefore far-reaching: they range from developing and implementing adequate water infrastructure systems (with corresponding governance, management and financing structures) that secure the availability and provide access to sufficient water resources in mega-urban agglomerations all the way to implementing adequate treatment technologies and the re-use of wastewaters.

The water management problems we are facing in megacities cannot be resolved with an isolated water-supply (input) and wastewater-discharge (output) perspective. Instead, we need to broaden the picture to the entire metabolism of the urban agglomeration and its surroundings, including the direct links between the water-, waste- and energy-cycles as well as the respective trade flows. The concept may also be extended to socio-economic issues, such as labor flows.

Some key research questions with respect to water and mega-urbanization are:

- How can a reliable water supply and sanitation structure be achieved in order to sustain the functioning of growing mega-urbanizations characterized by informal settlements? What are the alternatives to current infrastructures?
- How can new infrastructure strategies be implemented into sustainable urban planning and how can the transition from old to new be managed (including the associated institutional change)? What are the obstacles to the implementation of “integrated water solutions”?
- How can the water, carbon, and energy cycles be transformed from open to more closed cycles?

- How can risks related to water infrastructure and water supply, and health risks related to insufficient sanitation be minimized within megacities and among all the concerned social groups?
- How to integrate water supply and discharge / sanitation cycles into the "urban metabolism" including water (and virtual water / food), waste, carbon and energy cycles as well as trade flows?
- What are adequate governance, management and financing structures? Which factors drive institutional change in megacities?
- What are the interlinkages between water availability and rural-urban migration?

Global Climate Change, Vulnerability and Risk

The 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) shows that climate change is already taking place and will continue in the future. There is a high probability that the global mean temperature will increase between two and six degrees by 2100. The changes in mean temperature will have a severe impact on the water cycle. It is not only the change in precipitation patterns, but also the extent and severity of extreme events, putting humans and their properties as well as entire landscapes at risk. While some areas may experience increased water flows to such an extent that they will need to cope with flooding, other areas – often those with already scarce water resources – will experience even larger water shortages. Besides the direct effects of climate changes on water quantity and quality (e.g. the change in temperature and precipitation will have an effect on matter input from catchments), indirect effects will influence water quality: e.g. an increased use in pesticides will threaten water quality and ecosystem health. While climate research is capable to predict global mean values, the derivation of regionally disaggregated patterns and the determination of the probability of extreme events are by far more difficult. While the question of targeted monitoring for a better system understanding together with advanced modeling is discussed in the proposed Research Fields 4 and 5, issues on how to cope with the more frequently occurring extremes also need to be further investigated.

There is an urgent need to include the impacts of global climate change into water-related research in order to determine the need and the potential for adaptation to these new challenges. We need to develop indicators for determining spatial patterns of socio-economic and ecologic vulnerability in order to be able to propose adaptation measures or to determine the adaptive capacity of ecosystems and societies. Regarding flood risks, one possible measure is to take a closer look at the renaturation of flood plains and the creation of flood storage ponds and how and where such measures are most effective. Regarding drought risks, ecologically friendly storage and transportation mechanisms should be developed in order to store water for drier periods. Adaptive infrastructural measures and customized technical solutions will be a key aspect to secure the development and reduce the vulnerability of growing urban agglomerations towards floods and droughts. The water-related risks of economic and social globalization and climate change are not just natural phenomena: they are crucial factors affecting the well-being and the economic wealth of people; they also determine the vulnerability of poor people in particular. This holds true for global and climate change impacts on water-borne diseases and their spread and development in the future. Global change related risks may not only occur in form of sudden catastrophes induced by e.g. changes in weather patterns. Political decisions and economic trends may also lead to long-term risks and increase the vulnerability of people, societies and ecosystems. Such decision and trends are, for example, a shift from fossil fuel energy towards the production of bio-energy from crop production leading to competition for land, water and food, and hence impacting food security and threatening ecosystems. An unsustainable water management with respect to its quality or its quantity may risk people's access to safe water as well as ecosystem health and functioning.

What is therefore required is a broad analysis of factors determining global and climate change related hazards and humans' and societies' exposure to these hazards, as well as their capacities to cope with adverse effects stemming from water-related hazards. The adaptive capacity to cope with an increasing scarcity of water will pose a great humanitarian and social challenge in many of the poor countries and will require more than just the introduction of use-efficient technologies.

Some key research questions to be addressed in this field are:

- How can we better predict risks and impacts resulting from political decisions, climate change and economic forcing, taking into account the dynamic interactions and feedbacks of the various factors depending on the respective system under change?
- What are the coping strategies and adaptation measures needed to deal with these risks? How can we reduce the vulnerability towards global change impacts? How can we learn from experiences with extreme events and can this knowledge be transferred?
- What are the consequences of "boom" and "bust" cycles compared to more gradual changes (from trend- to event-based assessments)?
- What is the impact to be expected from an increasing number of extreme events, particularly on urban infrastructure? How can urban planners react to this?
- What are adequate institutional prerequisites and governance mechanisms to deal with the expected risks and vulnerabilities? What do risk-based management tools for decision-makers look like?

Obviously, all these challenges are interlinked: Climate change with regionally diverging and often negative effects (droughts, intense rain, floods etc.) as well as demographic change (migration, regionally shrinking or growing populations) and changing consumption patterns (development-induced increase in water consumption, efficiency-induced decrease in water consumption) lead to extraordinary challenges in long-term planning of infrastructure-based water services, especially for urban agglomerations. Beyond the technical and engineering issues, we expect the social aspects, e.g. the question of a fair water allocation to all societal groups or to activities that yield less economic benefits, to become increasingly important when available resources are limited. In dealing with all of these issues, we need to consider how we can take account of, avoid duplication and develop synergy with other water-related research and policy initiatives. As water is a determining factor when it comes to food, climate, and (mega-) urbanisation, water needs to be put into focus in the agricultural, climate and urban planning communities – water needs to move “out of the water box”!

Water – Energy - Nexus

Energy and water are closely interlinked in our current energy production and water supply systems, e.g. through the production of hydropower, the use of water for cooling in thermal power plants, and the energy needed in the production and treatment of drinking water and sewage. The global demand for both, water and energy are growing and are expected to grow at similar rates within the next years. We need to develop a better understanding of the interlinkages between water and energy in order to rethink how we can better manage the “water-energy-nexus”. An increased awareness of the respective connections and an improved valuation of our resources are needed. The development of innovative solutions for better managing these two resources is required.

Some key research questions in this field are as follows:

- What is the role of water in energy production today and in the future?
- How can we reduce the energy footprint of water management?
- How does climate change influence the water-energy-nexus
    - through mitigation (bio-energy, hydropower, etc.)?
    - through adaptation (cooling of power plants, solar energy production, alternative means of transport etc.)?

Research Field 2

Managing Water Beyond IWRM: Target Setting, Instrument Choice and Governance

Due to increasing water demand caused by global and climate change, and the existence of a multitude of use conflicts, the sustainable management of water is central for future societal developments. The goal is to promote economic and social developments by addressing and balancing diverse use interests, while simultaneously safeguarding water resources and related ecosystem processes. However, current water management practices are far from fulfilling these objectives for different reasons. In some cases, adequate management structures and techniques are not available while in other cases, existing management falls short in properly addressing the key problems as an integrated scientific basis to assist sustainable decision making, especially in emerging use conflicts, is lacking. In recent years some significant advancement in water management has been initiated by introducing the concept of Integrated Water Resources Management (IWRM), which has become a widely accepted guiding principle in the water sector. IWRM conceptually links societal, economical and ecological demands, and includes private and public stakeholders in the decision-making process. However, to make IWRM successfully implementable under complex and dynamic conditions a common understanding of the IWRM concept is required. We need another level of understanding with respect to target setting and indicators of success that suit the strongly varying demands of industrialized or developing countries. We need tools and instruments that are able to handle the complexities and uncertainties of the relevant processes leading to sustainable solutions, and governance allowing an effective implementation of measures. Water management needs to increasingly become a management of transition in order to deal with the dynamics triggered by global change impacts. Three fields are therefore proposed to be prioritized in a future research program:

Target setting - from the concept of sustainability to target setting in IWRM

An integrated system analysis and evaluation taking into account all involved sub-systems (economy, society, politics, ecosystems etc.) is an important prerequisite when developing suitable measures for water management. So far, ecosystem functions and services have not been adequately taken into account. However, a good understanding of the structure, function, and related services of surface and groundwater ecosystems as well as the multiple stressors impacting them is essential for the design of an adequate IWRM concept. One approach for the implementation of the IWRM concept is the Water Framework Directive as developed within the European Union. Even though some major progress has been made in the scientific underpinning of the concept of the “good status” of aquatic ecosystems as targeted in the European Water Framework Directive, some significant gaps remain. A good understanding of the aquatic ecosystems and their services that are in balance with the anticipated socio-economic development is needed. Multiple stresses (e.g. habitat degradation, eutrophication, toxic chemicals, invasive species, and overexploitation of water resources) concurrently impact the ecological status while diagnostic tools to identify and prioritize relevant stressors and interactions are missing. We still lack predictive, i.e. mechanistic models to forecast and evaluate changes in ecosystem processes and services under (rapidly) changing environmental conditions and models that are able to predict and evaluate the responses of hydrological and ecological systems to management measures. Indicator concepts for determining a good ecological status of groundwater remain undefined, yet they could facilitate such predictive approaches. Furthermore, our current IWRM concepts either assume a “linear” cause-effect relationship which of course can seldom be encountered in real-world systems, or they are described as a cycle with various feedback loops, yet they lack the necessary tools to take these feedbacks into account. We frequently see delay effects, hysteresis and feedback processes as well as non-linear responses between alterations in the water system and the related response of the ecosystem. The same holds true for the related socio-economic consequences and the social and political responses, which need to be included into analyses and prognoses.

Consequently, we need new ways to analyse multiply stressed hydrological and ecological systems and to quantify competing/synergetic uses of water resources and ecosystem services e.g. through specifically designed analytical tools and linked experimental – joint effect modelling studies. We need advanced, long-term observatory and monitoring approaches to identify spatially differentiated environmental/ecological thresholds and regime shifts as well as major delay and feedback effects and combined effects of multiple stressors. We need to develop ways to integrate ecosystem services into large-scale IWRM and we need to understand the role of spatial heterogeneity for the protection of biodiversity and species migration. We need to expand our classical concentration-based conservation approach to an integrated management approach which comprises external (e.g. reduction of emissions into the water bodies) as well as internal measures within the surface- and groundwater bodies; we need to conceptually link natural and technical systems, where both contribute to a “combined optimum”. Also, we need to conceptually link aquatic ecosystem functions with terrestrial ecosystems (as a result of land use and soil functioning as discussed in Research Field 3) and link them to current and anticipated socio-economic development. We need to quantify the economic value of the ecosystem services we use for certain purposes directly or indirectly. Finally, we need to move from a sectoral water management approach towards a coordinated management of landscapes and natural and man-made resources (e.g. water, waste and energy) that also takes into account the concepts of green and blue water, and virtual water (see RF 1).

Some key research questions to be discussed are:

- What are adequate ways of standard setting with respect to water quality and quantity taking into account the status and functions of aquatic ecosystems and socio-economic development? How can these standards be met?
- What are efficient and effective ways to integrate sectoral knowledge from different disciplines in order to improve adaptive management strategies?
- What would be the characteristics of a new generation of data, information and decision support systems that would comply with the set standards?
- What are the necessary eco-hydrological concepts for achieving ecological and use-related requirements? How can the different uses be balanced?

- How can we assess the synergistic, antagonistic and additive effects of multiple stressors, including climate change, on biodiversity, ecosystem processes and ecosystem services?
- How can the ecosystem service approach be used to define specific targets in IWRM applied to the large scale, in particular in emerging use conflicts?
- What are the necessary concepts, tools and measures, and political and institutional prerequisites to achieve a coordinated and integrated management of landscapes and resources (natural and man-made)?

Defining measures and choosing instruments: from theory to practice

In order to achieve the set targets, effective measures need to be identified and implemented. Surface and ground waters serve a broad range of technical and socio-economic uses including commercial shipping, hydropower generation, and water abstraction for various purposes, wastewater discharge, tourism, and the extraction of construction materials. These uses can have direct or indirect impacts on the environment and the society, which are often neglected in the planning process. As a consequence, remediation measures may become necessary and cause costs which can surmount the socio-economic benefit of the respective use. We therefore need to consider all impacts that active measures can provoke, including potential long-term deterioration, into cost and benefit planning. This requires advanced sets of criteria for the planning and selection of measures, and a more encompassing cost-benefit-analysis including the value of ecosystem services. This leads to more complex dimensions of optimisation with more degrees of freedom but also potentially more effective solutions. We need decision-support systems which combine classical cost-benefit with participatory multi-criteria analyses addressing different levels of uncertainties related to the measures proposed in order to achieve cost-efficient combinations of measures.

For the effective implementation of measures aiming at a balanced allocation and protection of water resources, the applied instruments need to be carefully chosen and designed. Such water-related instruments include regulation (technical standards, performance standards, etc.), quotas, access rules and allocation procedures, as well as economic instruments (especially pricing instruments and payments for ecosystem services). These instruments need to be based on full cost recovery, the precautionary, as well as the polluter pays-principle.

As an example for the choice of instruments contained in the economic academic literature, the problem of achieving targets is often considered to be solved by pricing. In practice prices have to serve several, partly conflicting purposes: they have to ensure sufficient financing of water service related infrastructure, they have to provide incentives for an efficient use of scarce resources, and they have to reflect aspects of fairness and distributional justice. Thus, pricing water services typically addresses the challenge of multiple objectives: ecological sustainability, economic efficiency, financial sustainability and social concerns. Furthermore, there are different institutional types of pricing, such as fees, taxes and charges, but also tradable rights for different water-related services. While academic research up to now focuses on more singular approaches, in practice we observe a policy mix with overlapping instruments. This reality needs to be addressed and we need to bridge the gap between theory and real-life solutions in this particular field.

For a sustainable water management that is able to successfully adapt to the dynamic development of socio-economic and environmental conditions, technological and logistical innovations along the water supply chain play a key role for the optimisation process of IWRM strategies. Areas for necessary technological developments include energy efficiency of waste water treatment, concepts and technologies for closing water use cycles, water infrastructures for water supply and sanitation/sewage treatment, adaptable storage capacities for areas of variable water availability, technologies for increasing agricultural productivity and irrigation efficiency (see also RF 1 & 6).

Some key research questions to be discussed are:

- What legal and economic instruments are available and under which conditions do they work in an effective policy mix?
- Is pricing an alternative for allocating water resources in an efficient manner and how can pricing mechanisms be adapted according to the given cultural and social conditions?
- How can aquatic ecosystems be included into pricing strategies in most effective and easy-to-handle manner?
- How can technical measures and economic and legal instruments be complemented in a cost-effective manner in their specific contexts?
- How can we discuss allocation at national or basin scale when different scales (e.g. global virtual water flows) come into play?
- What are the necessary tools and technologies to support the successful implementation of IWRM?

Water governance: Adequate structures and processes for decision support and management

An effective and efficient water management cannot be achieved without the existence of an appropriate governance structure. Water governance refers to the way water resources are managed, namely who decides on what and according to which rules.

In the analysis and design of water governance structures, we need to address problems of fit, interplay and scale. In order to implement a concept for water or river basin management, the challenge is to better match hydrological and political systems (problems of spatial fit). Furthermore, policy fields that are closely related to water management need to be included into the decision-making process at the various levels (e.g. agriculture, regulation of chemicals, biodiversity) (problems of horizontal institutional interplay). In addition, mechanisms are required that allow for the coordination of decision-making competences and management practices among the various administrative levels (problems of scale and vertical institutional interplay). For instance, within Europe there still is a discrepancy between the advanced regulatory framework of the EU Water Framework Directive and national and sub-national institutional settings, which are inadequately structured for its implementation, (e.g. multi-level federal structures limit the effectiveness of integrated river basin management).

Additionally, as many political and economic fields are becoming increasingly interlinked on a national as well as an international level, governance structures for the management of common pool resources such as water will have to respond accordingly. This is particularly relevant as many societies are currently facing socio-economic transformation processes which need to be reflected in changes of the respective governance system. In developed countries, this refers to the provision of water which is often changing from a more public towards a more private supply; in the former socialist countries, this refers to the transformation of institutions and governance structures, and the implementation of new regulations. In some developing countries adequate governance structures are missing so far and need to be created while a strong state and financial capacities are lacking. As a simple example, while observations at the global scale reveal that large investments for water infrastructures are required, there is a lack of adequate governance structures for mobilizing these investments and for putting them effectively into place.

In order to develop adequate governance systems, we need a profound understanding about their functioning and design. We need to take account of the concepts of public goods and common pool resources and to include the different actors and stakeholders through participatory processes. We need to create decision-making arenas and adequate legal and institutional framework conditions at various governmental levels (i.e. global/European, national, regional, sub-regional etc.). We need to consider multiple problems of scale, fit, and interplay. Also, we need adequate governance solutions for trans-boundary water management and modes of conflict resolution. When we move towards finding concepts for adequate governance structures and processes, we need to think about how to move from the current status to the targeted governance system (transition management). We need methodologies that allow us to transfer the developed concepts and strategies from one catchment to another based on context sensitive analyses and empirically founded recommendations. Last but not least, we need to develop and implement adequate concepts of capacity development, in order to improve governance structures. Some key research questions are:

- What are effective and/or alternative governance structures for the implementation of IWRM and how can existing structures be transformed?
- Under which circumstances is IWRM an effective strategy leading to more favourable solutions? Does IWRM open the perspective to solve trans-boundary conflicts?
- What are the major drivers of water management beyond the water sector (“out of the water box”)?
- (How) Can the inter- and trans-disciplinary approach that is embedded in the IWRM concept be operationalized – is there an optimal degree of inter- and trans-disciplinarity? Should we move towards an integrated and coordinated landscape and resources management? What would the required governance structures to achieve this?
- What are adequate methodologies to transfer the developed structures, strategies and concepts from one system to another?

Research Field 3

Understanding Matter Fluxes at Catchment Scale: Safeguarding Our Health and the Environment

A growing global population comes along with the release of a multitude of compounds of largely unknown fate into the water cycle. One of the major causes which compromise the quality of natural waters originates from agro-chemicals applied to soils which percolate to the unsaturated zone, the groundwater and the surface water system. The expected land use changes together with an increase in food and energy production will eventually lead to an increased chemical load and also to an increased pressure on the protective zones left. Another cause of additional stress on the water cycle comes from the significant increase in urbanization at the global scale that we observe mostly outside Europe. Atmospheric transport and deposition cause ubiquitous distribution of pollutants in water and in soils. Changes in water quality are often of a long-term nature and not easily reversible, mostly because of the size of water bodies, long mean residence times within the system (e.g. groundwater), or due to large storage capacities of compartments (e.g. soils and sediments). In order to be able to distinguish between problems at local scale and those at regional scale, we need to conceptually move beyond the common point-scale concentration-based assessment methods and complement them with dynamic and spatially integrative mass flux assessments. This will eventually lead to a better consistency with regulatory targets (e.g. EU-Water Framework Directive) and a better overall status of water quality and ecosystem functioning on the large scale. In order to support a prospective management of water, we need to focus our effort on an improved understanding of the long-term development of the relevant matter fluxes at catchment and basin scale together with the expected impacts of the anticipated changes described above. However, while matter fluxes can only be described on a larger scale on the basis of water fluxes, we still do not sufficiently understand water fluxes at the catchment scale. At the catchment scale water balances are a crude approximation based on a simple input-output concept, but they are not suitable for use as the driver of matter fluxes within the different compartments and reactive zones of a given catchment.

So far, we have only very limited methods to quantitatively observe, measure or even alter the fate of large-scale matter fluxes. We have therefore prioritized the key research areas according to their relevance in and beyond Europe today. Obviously, these priorities may differ in various parts of the world and priorities may also change over time.

Water Fluxes at Catchment Scale: Setting the Frame for the Understanding of Matter Fluxes

In order to understand the hydrological and ecological functioning of a catchment, the relevant water fluxes need to be analyzed, including precipitation, evapotranspiration, surface-runoff generation and infiltration, soil water movement, groundwater and river dynamics, all the way to the discharge into surface waters including the sea. The impacts of global and climate change on water cycling and feedbacks and interactions between the different hydrological processes need to be included into these analyses. This knowledge provides the basis for understanding water-flux driven processes, such as matter fluxes, transport and accumulation as well as transformation of chemicals and nutrients in the environment. Important questions are:

- What is the role of the soil-plant-atmosphere interface and the hyporheic zone within the hydrological cycle and how can we adequately measure and model the relevant processes at a larger scale (e.g. hillslope/catchment/basin)?
- How do climate and land use changes alter the hydrological fluxes and how do these changes feed back into the regional climate?
- How can we quantify the uncertainties of water flux estimations based on measurements and modeling?

Soil functions as a key player in the hydrologic cycle – are they robust in the light of changing land use and climate?

There is a close link between soil functions and the vulnerability of ground- and surface waters, e.g. improper land use management in combination with a changing climate enhances the potential for surface runoff, erosion, salinisation and leaching. The resulting flow of matter affects the quality of groundwater and surface waters. An unresolved issue at the landscape level is the quantity and quality of matter flow across the various reactive zones between soil-plant systems and the different water bodies (vadose zone, capillary fringe, hyporheic zone, and coastal zone). We are convinced that the quantification of turnover rates and fluxes within and across these critical zones is crucial for the understanding and determination of mass balances of solutes in our catchments. This is of particular relevance in areas where groundwater resources serve as the major source for drinking water supply. Thus, the following issues have to be addressed:

- What is the role of the different reactive zones at hydro-interfaces for water quality?
- What are the major risks for and expected dynamics of water-soil relationships resulting from increasing land use intensity and changing climate (reliability of filter functions of soils)?
- What are adequate management measures to protect soil functioning (e.g. filtration, buffering, transformation of matter) under multiple stresses?
- How to approach risks across scales: Can we provide perspectives from the local to the landscape level?
- What is the role of the coastal zone in matter fluxes between land and ocean?
- To what extent can land management, innovative agro-technology and ecological engineering provide strategies to counteract expected negative effects on ground- and surface waters?

Urban matter fluxes: What is essential to manage their impact on receiving waters?

In urban regions, water and matter fluxes are tightly coupled. The dynamics of the nutrient loads are much more pronounced than those of diffuse sources. Though agriculture is the dominant source regarding average loads, due to the distinct dynamics of the urban wastewater systems the latter may substantially contribute to the pollution of water bodies with short-term peak loads. In water scarce areas urban regions may even contribute the largest part of the river flow. Urban regions introduce micro-pollutants, nano-particles, antibiotic resistant pathogens and endocrine disruptors, and thus potentially compromise raw water quality for subsequent purposes. Leakages in the urban water infrastructure may threaten the quality of groundwater below and downstream of the urban settlement. Large amounts of solid wastes generated in urban areas (e.g. from the demolition of buildings, incineration of wastes, metal production) are recycled e.g. for road construction and landscaping, and in the long-term substantially contribute to matter fluxes by emitting chemical substances into the water cycle.

In this context the following research questions are of specific interest:

- What knowledge is required for the development of models of urban water systems reflecting their dynamic interaction with groundwater and surface waters?
- What are suitable criteria for informed decision-making in urban water management integrating specific ecologic, economic and societal conditions?
- Do we have technologies available or are there system alternatives to be developed in order to control the matter fluxes of urban water systems?
- What are the potential risks related to hygiene and pathogens under the conditions of climate change?

Water quality – managing unintended effects menacing human uses and ecosystems

Water quality deteriorated by pollution may imperil both direct human uses and the functionality of ecosystems. While acute toxicity in surface waters is becoming rare, sub-lethal and long-term effects affecting the fitness and competiveness of sensitive species are of increasing concern. In addition, questions about carbon, nitrogen and phosphorus in the water cycle remain unresolved. Due to the multitude of substances of potential and prevailing concern (e.g. chemicals, humic substances), and the additional risk through the mixing of pollutants, some of the questions which need to be answered to increase the usefulness of management tools are:

- How to identify those primary and emerging pollutants and relevant metabolites in the water cycle which pose a significant risk to human uses and ecosystem functioning?
- How can we diagnose relevant sub-lethal effects on an organism and community level?
- Which compound and system properties determine the bioavailability, persistence and attenuation of priority substances?
- How can the identified pollutants be prioritized with respect to management actions and regulations also considering their bioavailability and persistence?
- What role do changes in the freshwater cycle play in the global and regional carbon, nitrogen and phosphorous cycles? How sensitive do different ecosystem types respond to global change? How does the landscape configuration control matter fluxes at the catchment scale?

- What knowledge, methods and tools are needed to predict long term risks to humans and the environment and the effectiveness of management measures under conditions of multiple stresses and changing boundary conditions?
- How can we adequately assess and manage the effects of chemical substances released into the environment in an integrated manner when taking into account the uncertainty of predictions related to the interaction and long-term chronic effects of chemicals?
- What are the necessary incentives and effective management instruments in order to reduce the emission of pollutants into the environment?

Research Field 4

New Approaches to Observation, Exploration and Data Assimilation in Water Research

System-oriented research within long-term observatories and monitoring programs are fundamental for detecting environmental change. The long-term data obtained from scientific monitoring also provides the opportunity to analyse the response of the terrestrial system to changes in the water cycle and water management, and to study system inertia and complex feedback mechanisms between the various compartments and ecosystems involved in the water cycle. The long-term interdisciplinary approach applied across all spatial scales allows us to analyse and predict water-related processes, and to develop solutions for complex hydrological systems. They are essential for the protection of aquatic ecosystems and the development of sustainable water management strategies.

In addition to selected and intensively equipped observatory sites, flexible-to-use measurement and monitoring systems that can be set up in many places for short periods of times, e.g. during focussed measurement campaigns, are needed. Such systems allow us to acquire information on e.g. subsurface properties or system variables in response to temporal events such as floods or chemical spills.

Supported by advanced data management, the combination of both, long-term site specific observatories and flexible-to-use systems provide the required system understanding as relevant for watershed management based on reliable predictions of future system states. They bridge the gap between empirical work, laboratory experiments and modelling approaches.

Despite the fact that long-term observatories are a key to detecting environmental change, only very few long-term observatory and monitoring programs do exist, most of them focussing on single research sectors or compartments. Such examples are the federal surface water and groundwater monitoring programs, the global scale FLUXNET network focussing on carbon dioxide and water vapour exchange between the land surface and atmosphere, GLEON, the Global Lake Environmental Observatory Network, or LTER in the US and in Europe with a focus on ecological research.

Observation & Exploration

In order to evaluate the impact of Global Change processes on the quantity and quality of water resources advanced multi-compartmental, multi-scale observatories are needed. These observatories should be designed with a clear scientific focus and implemented in a robust and flexible way in order to allow for upcoming new measurement and sensor technologies to be easily implemented.

Development of system understanding: We need to develop observation and monitoring concepts that will allow us to link system understanding across multiple environmental compartments. While the individual monitoring of changes in climatic, biotic and anthropogenic forcing, or individual states and fluxes within the groundwater-soil-plant-atmosphere-continuum is insufficient, we rather need a holistic approach as, for example, suggested within the “Critical Zone (CZ)” concept by the NRC in 2001 and/or as implemented in the TERENO catchments (www.tereno.net). During the last few years it has been well recognized that the quantity and quality of water as well as its related fluxes (water, energy, solute, gas and organism fluxes) is governed by complex interactions of hydrological, biogeochemical, physical and ecological processes which predominantly take place at system interfaces between the different environmental compartments and along spatial structures at scales ranging from the pore to the catchment scale. Furthermore, anthropogenic aspects and societal decisions strongly influence the environmental system, and the adequate integration of the human dimension into integrated environmental observation is a largely unresolved question. In addition, boundary conditions set the frame for the analysed system and strongly determine its evolution and dynamic behaviour, and therefore the analysis' outcome. We therefore need to move from only monitoring state variables and local system states towards the observation of fluxes, their spatial variability and temporal dynamics. This will allow us to analyze a broad range of complex process-pattern-interactions and to extract dominant process controls at different spatial scales.

Bridging scale and data-model gaps: The complexity of the hydrological system results from non-linear interactions between the different environmental compartments taking place across a wide range of spatial and temporal scales. Nested monitoring approaches and the use of advanced methods are very promising concepts to acquire information across the relevant scales and to fill knowledge gaps regarding compartment interactions and scale dependencies. The integration of data and models from different scientific disciplines, together with the need to make use of the vast knowledge gained in detailed process investigations requires new strategies for data collection, information processing and knowledge communication in order to improve catchment-scale water management concepts. Uncertainties in the description of environmental systems and in the acquired data need to be quantified, e.g. with the help of stochastic modelling approaches such as sequential data assimilation techniques. Uncertainty studies provide essential information on the value of data and help to optimise monitoring strategies (e.g. nested observation approaches). New model driven measurement concepts and sensor technologies need to be integrated into monitoring strategies for obtaining the maximum possible information at minimum costs.

Integrated Observatories: Significant advances in understanding water-related processes have been made in small-scale laboratory and field experiments over the past decades. However, significant knowledge gaps remain between the process understanding gained in controlled laboratory experiments and the system description and prediction at the field or regional scale. We need a new generation of modern exploration and observation approaches and methods which enable us to verify and validate interdisciplinary concepts, to observe and analyse complex system responses, and to link observations made in different compartments. The improved system understanding will enable us to develop and adjust management and adaptation strategies to changes in the water cycle. Furthermore, we need to acquire the ability to partially manipulate forcing variables at the larger scale in order to identify specific system responses and causalities. Observatories and experimental sites such as the TERENO initiative and the “Jena Experiment” (www2.uni-jena.de/biologie/ecology/biodiv/index.html) may serve as examples of how to link-up all experiments to specifically equipped, long-term, intensively monitored reference sites. Observatories should serve as a platform not only to exchange and link data and information also with other observatories/networks, but also to link and exchange ideas, tools and people.

Such observation and exploration facilities should allow us to analyse questions such as:

- Can we define “core data“ to be collected within the integrated observatories that is essential to and integrates the different disciplines of the water science community and related disciplines?
- How can we optimize exploration and monitoring strategies that allow us to analyse complex system responses and to validate concepts of interacting processes across different compartments?
- What kind of large-scale experimental facility network is required to advance our mechanistic understanding of entire hydrological and ecological systems under human and Global Change influence?
- What and where are the “hot spots” of system behaviour?
- To what degree does functional heterogeneity (e.g. time series of groundwater heads) reflect structural heterogeneity (e.g. aquifer properties)? How can we identify the interactions between structural and functional heterogeneity?
- How many degrees of freedom does a given system actually exhibit? Does the intrinsic dimensionality of a hydrological system increase with increasing anthropogenic pressure?
- What is the relevant time and space scale of single processes and their feedbacks?
- What is the appropriate model structure to describe the observed dynamics for given time and spatial scales? Can suitable model structures be extracted from the observed data?
- How can we bring together the knowledge gained in different scientific disciplines from a data and model use perspective in order to improve catchment scale management concepts?
- How can we adequately integrate socio-economic sciences into integrated environmental observation and modelling? How can we bridge the conceptual gaps between natural and socio-economic sciences?
- How can multiple data from small to large spatial and temporal scales be integrated to reach a deep understanding and a significantly increased predictability of regional hydrological change?

Information Infrastructures

As a consequence of the developments in high-resolution monitoring and remote sensing technologies huge amounts of data will be available for the characterisation of environmental systems. In order to efficiently use these data for hydrological analyses new data management concepts, data processing and interfacing tools, as well as data integration and assimilation methods need to be developed

Furthermore, as we call for long-term observation and monitoring, we need to consider the large amounts of water-related data and long data series that have already been collected and, in principle, are available in Germany, Europe and globally. As they are a valuable source of information about developments in the past, they are also fundamental for solving water-related problems of today. We need to find ways of making use of these data. However, there are two obstacles: Firstly, existing data have been collected and are stored by different institutions (e.g. universities, agencies, companies) and quite some effort would be needed to collect and structure these data, e.g. in a newly built data base such as that of the Global Runoff Data Center (GRDC). Secondly, the existing data sets vary in their quality. Some are screened for errors, some are not, and information on the data screening is not available. Hence, we do not know the suitability of the data for current application and post data-screening requires a large manual effort. We need to therefore share developed screening procedures and meta data on possible errors in data sets in a community effort.

Data management techniques: Modern measurement and monitoring systems provide continuous (e.g. sensors) and high-resolution (e.g. airborne remote sensing) data streams. Data management techniques are required which, on the one hand, allow automated data storage e.g. from on-line systems and, at the same time, assure data quality norms.

Web Services need to be developed and installed for retrieving data through the internet. Data processing will become increasingly important as the sources of data will span a large range of different temporal and spatial scales. Existing web-based Information Infrastructures as targeted by initiatives as GEOSS (http://www.earthobservations.org/), INSPIRE (http://www.inspire-geoportal.eu/), and GMES (http://www.gmes.info/), LIFEWATCH (http://www.lifewatch.eu/) and CUAHSI's new HydroDesktop (http://hydrodesktop.codeplex.com), and as recently announced as a key scientific challenge by the German Science Foundation (DFG) need to be enhanced to support scientific data management, dissemination and exploration. Online processing and decision support services should provide the various stakeholders a straight forward access to scientific results.

Open source data provision: Publicly funded scientists should be made responsible for providing all collected data to the science community free of charge and for avoiding the loss of data. Large amounts of tax money are wasted by not following this principle. Hence, clear rules with adequate consequences (e.g. prohibiting further funding) need to be set for making data available within a specified format (see web services) and within a certain time.

Data processing: Data from different compartments (atmosphere, land surface, vegetation, soil, surface water, aquifers) and socio-economic investigations need to be processed for different purposes of process-based and process-oriented as well as rule-based simulators. Data management is to provide information for better understanding the functioning of environmental systems and for model development with profound predictability (see Research Field 2 concerning community modelling).

Integration of diverse data from different sources such as monitoring and modelling is important to retrieve additional knowledge from the original information. A challenge for data assimilation is to level out the heterogeneity of information in time and space, resolution and uncertainty. To ease fusion of data stemming from distributed data sources, specific semantic reference systems (onthologies) and related reasoning methodologies need to be provided. Again European and international initiatives such as INSPIRE and GEOSS for data organisation as well as quick data search semantic rules and onthologies may serve as reference when developing solutions for the specific requirements on environmental data. Common data formats (e.g. WaterML for hydrology, GML, NetCDF, HDF, etc.) could offer a first handle to these research activities. In addition, appropriate visualization tools need to be developed or adapted in order to handle the amount and heterogeneity of environmental data.

Integrated models do not only refer to the integration of the different natural sciences disciplines. In order to move beyond the scientific exercise and make our models adequate tools for decision support, we need to find ways of integrating socio-economic data and political aspects into our models. Only by doing so, will we be able to develop more realistic scenarios and make more reliable predictions into the future.

Some key questions for Information Infrastructures in water research are the following:

- How can we deal with the vast amount of data collected, while simultaneously allowing advanced scientific data management, assuring data quality, and providing decision makers access to scientific results?
- How can data quality be defined and propagated?
- How can the methodologies to support assimilations across various scales be improved?
- What are common hydro-interfaces and hydro-semantics? What are hydro-socio-economic interfaces?
- How can we adequately process data for the different purposes needed?
- How can we make use of data stemming from various sources, and hence exhibiting large heterogeneities in time, space, resolution and uncertainty?
- How can we retrieve socio-economic data and adequately process and integrate these data to make them compatible for integrated hydrological models?
- What does a suitable web-based tool look like that is able to support management decisions based on the assimilated data?
- What could a common organisational frame (rules, licensing, etc.) for data use look like?
- How can we insure the long-term availability of the data sets?

Research Field 5

A Community Effort Towards Model Development and Data Integration for Water Science

The water science community has a long tradition in the development of a wide range of modeling tools. Most of these tools originate from specific process or system studies at various scales and various levels of complexity. They have led to a variety of approaches ranging from data driven input-output models to physically-based conceptual or partial differential equation based (PDE) concepts. It is generally accepted that not one single model can be efficiently applied to the full range of water related problems encountered in real-world systems. Ideally, each model represents a specific simplification and interpretation of reality according to the investigated problem and requires a specific set of parameters. This has so far been the general understanding within the scientific hydrologic community. Consequently, with the exception of one or two commercial packages, in the past only little attention has been given to the design and development of a more widely applicable community model system (not a community model!).

However, in the meantime, hydrologic modeling is facing several outstanding new challenges in the context of global change, including the development of water management solutions both in terms of quantity and quality. Reliable models of adequate complexity are needed ("[…] Simple, but no simpler"; Einstein, 1933) since prediction requirements now reach beyond the range of available observations in time and in space, and may require the incorporation of unprecedented natural or man-made changes to the system parameters, boundary conditions and also the system structure.

Today, the hydrologic science community does not yet have the necessary tools and the experience to produce these kinds of predictions or projections with the required level of confidence. We will need hydrological models not only with improved predictive capabilities, in high spatial resolution and with extended areal coverage, but eventually also with new conceptual model and software structures – new structures that range beyond simple model-to-model cross-compartmental coupling. The consistent multi-scale integration of all hydrological and socio-economic processes that are relevant for a particular problem will be one of the most challenging problems to solve. This can only be achieved by a thorough analysis of the hydrological system, the identification of relevant processes, and the establishment of new conceptual approaches and software structures for adequately representing these processes at the targeted scale.

The key question is: Can all this be achieved with the "single problem – single model" approach employed so far? Or else, do we need a community effort – not a community model - in order to advance the modelling science beyond individual improvements of specific model capabilities? Unlike the climate modeling community, the hydrology community has no experience yet in organizing itself with respect to "long-term division of work" and will eventually need a fundamental discussion on how to tackle the new challenges in a community effort.

Hydrological modeling meeting real-world systems

Development of highly flexible model structures to meet specific demands: Most of the existing hydrological models are optimized for a certain process or compartment (e.g. good representation of surface flow but weak representation of soil moisture). For an integrated representation of the major hydrologic compartments (e.g. groundwater, soil, and surface water) at catchment and basin scale together with the relevant processes at the land surface (evaporation, transpiration by plants), atmosphere, and anthroposphere we need to develop new highly flexible model structures which include mass and energy balances (e.g. to connect to the climate community) as well as biological processes rather than just coupling existing model components. These new structures should overcome the problems we face today in the definition of coupling variables, in joining different levels of model complexity, in formulating consistent boundary conditions, in closing scale gaps in the space and time domains, as well as in identifying model incompatibilities.

Due to the variety of water management problems, different levels of model complexities must be available to fit the specific demand. In addition to improve the model capabilities for a holistic system understanding, the next generation of hydrological models should emphasize the practical applicability to real-world research problems (e.g. the representation of the transient character of hydrosystems in hydrological models influenced by global change and the coupling of the climate – vegetation - surface water – soil - groundwater continuum). The applicability requirements need to include issues like data availability, data value considerations and the quantification of uncertainties.

Meeting the requirements of the multi-scale nature of hydrological systems: Hydrological systems are of a multi-scale nature - driven by large scale phenomena such as climate and land use change, small scale processes e.g. within the soil-groundwater-interface may also be relevant for the overall system response. A multi-scale approach for hydrological modeling needs to bridge these scale gaps to improve the model predictability with respect to the cycles of water, chemicals, energy, and ecosystem responses at regional scale (i.e. catchments).

Data integration and assimilation functionalities will be increasingly important to hydrological modeling in the future (see Research Field 4). This has to go together with additional efforts to establish long-term hydrological observatories (e.g. the Helmholtz TERENO sites) which can provide the type and quality of data basis needed to drive the next generation of hydrological models (see Research Field 4 on observation) At the same time we need to put a focus on the compatibility of measured data and the models that process these data. We need model concepts that are able to process the data collected in an optimal way and - vice versa - monitoring concepts are needed that fit the models. This refers to e.g. the scales of data and models. “Scale” in this case refers not only to the horizontal but also the vertical scale (from geophysics to satellite data) and the time scale. It also refers, not only to the scales of models and data, but also to the consistency of data formats and model semantics (see Research Field 4).

When discussing the issue of a community effort for hydrological modeling, we need to keep in mind that there are different kinds of models that stem from different backgrounds and therefore have different underlying concepts (e.g. stochastic versus PDE-based models; conceptual versus input-output /black box-models; land surface versus river basin models). When coupling the different models, we need to decide first what the aim of the coupling is and scale gaps need to be resolved!

We believe that this discussion should address the following key research items:

- What would innovative model structures look like that meet the demands of real-world problems with a flexible integration of different compartments and processes?
- How can the different space and time scales in hydrological systems be reflected in these models? How can they be made adaptable to different levels of complexity according to problem structure and data availability?
- How can we provide the type and quality of data that is compatible to this new generation of integrated hydrological models?

Hydrological benchmarking efforts

We propose a community initiative in hydrological benchmarking. Developing benchmark tests are an appropriate and efficient tool for code comparison and joint model development. Benchmarking facilities should aim at both simplified and real-world test scenarios. Academic test cases are useful e.g. for the analysis of complex system responses, to evaluate the importance of individual processes and coupling phenomena. The development of real-world benchmarks (e.g. intensively equipped catchments) goes beyond numerical simulation and comprises data integration and assimilation. We believe that hydrological benchmarking is a key element within the proposed model development community effort – it should be organized at the national and the international level.

In Germany, given a broad expertise in modeling the earth system's related water, mass and energy fluxes, we believe that through an extensive, coordinated effort it is possible to set up a common, open access framework for modeling and predicting the earth's hydrologic cycle. This framework will consist of a modeling and software framework for a close integration of existing and future knowledge of the most relevant hydrology-related processes. The framework will provide a flexible coupling scheme for interchangeable hydrological as well as hydrology-related model components using defined interfaces, a benchmarking facility for model testing and evaluation, a development environment of efficient numerical solvers and preconditioners based on parallel computing capabilities to allow the use of exabyte computing environments, a development environment of new strategies for the application of existing and new data sources for parameter estimation and data assimilation; and an integrated sensitivity and uncertainty analysis environment. From the beginning, this national initiative should develop close links to the international hydrologic community at all levels and take a leading role in some of the key research areas.

A benchmarking initiative could provide answers to the following questions:

- Which models should be applied to what kind of questions?
- What are the strengths and weaknesses of certain model approaches?
- How can we combine the advantages of different model concepts for a better overall result?
- What could a framework for a community modeling effort look like that takes into account the above mentioned criteria?

A community effort on hydrological model development and model benchmarking should focus on developing a framework which

- defines interfaces to create an environment for new components
- provides new process descriptions
- serves as a basis for benchmarking (get different models of similar type together)
- provides access to common data sets and optimally uses these data for model calibration and data assimilation
- integrates with other disciplines (create model interfaces) in order to solve future challenges, especially vegetation, atmosphere, economics and social sciences
- supplies model developers from hydrology and other disciplines with all the external data (as output from other models) needed for the improvement of process description
- prevents developers from being forced anymore to start from scratch.

In order to allow for free and easy intercommunication and interaction of a hydrological modeler community, a collective internet platform is necessary that allows the management of various benchmarking projects, including joint model development, code comparison, data exchange, documentation and discussion.

Research Field 6

Water Scarcity: A Circum-Mediterranean Research Initiative

Today, problems resulting from water scarcity are considered the major challenge for about one third of the world's population. In the less developed countries, water is often the limiting factor for crop production, and consequently for food supply. Water scarcity leads to significant sanitation problems and generally limits economic development. Population growth, with a projected 9 billion people on the planet by 2050, together with an expected increase in per capita meat consumption will significantly sharpen the water scarcity problem. In addition, the anticipated reduction of groundwater recharge due to climate change of up to 50% and beyond in many of today's semi-arid zones will exacerbate the occurring problems. Water pollution resulting from municipal and industrial waste water, drainage water from intensive agriculture and salination resulting from inadequate irrigation or over-extraction of groundwater resources additionally impair the availability of fresh water resources. The increased water scarcity will also affect the economies of developed countries, including all sectors from agriculture, water supply and waste water, transportation and tourism, through to the energy sector. In today's world-wide network of trade the aggravating water scarcity in some parts of the world will lead to an increased demand for agricultural products from other parts of the world, resulting in a significant increase in virtual water trade.

One of the most imperiled regions in the world concerning present and future water scarcity is the Circum-Mediterranean region comprising the Southern European, North-African and the Near and Middle Eastern countries. This region is characterized by an extremely fast growing population in the North-African and the Near and Middle Eastern countries with an expected tripling in food demand over the next 50 years. Simultaneously, the economies of most Southern European states which today strongly depend on agriculture and tourism will face a fundamental change, if the available water resources will decrease by more than 50 % within the next 50-100 years, as indicated by the most recent climate projections, for example as stated by the National Center for Atmospheric Research in 2010. Furthermore, the Mediterranean coastal region represents one of the most densely populated regions in the world with currently 180 million inhabitants and 250 million expected by 2025. This population growth will result in a growing water demand and tremendous waste water and regionally concentrated pollution problems. Some megacities in the Mediterranean area still discharge large parts of their untreated waste water into the rivers and the sea, having a major impact on the ecology of the Mediterranean Sea. These developments are accentuated by the fact that in many of the Mediterranean countries, the natural renewable water resources are fully exploited or over-exploited already today, while at the same time, the Mediterranean area is a global hot spot of freshwater biodiversity, with a high proportion of endemic and endangered species. Hence, the Mediterranean area is a high priority region for freshwater conservation and restoration.

However, at the same time the Circum-Mediterranean region offers extraordinary development opportunities. The Eastern and Southern region hosts more than 30 % of today's world fossil oil and gas reserves and comprises some of the fastest growing urban and industrial development areas in the world. The South European coast represents one of the largest private property and tourism markets in the world. Ambitious plans exist for a series of North African countries to become energetically self-sufficient and on top of that to cover 15 % of the future European electricity demand based on a network of renewable solar energy plants spanning the Southern Mediterranean basin.

All the existing activities and the new opportunities assume the availability of water, either from rivers, from groundwater, desalination plants or from wastewater- and irrigation-return, which cannot be taken for granted considering the long-term resources projections. The expected increase in scarcity will therefore be a forceful driver for the introduction of new water-efficient technologies in all sectors, and also for a better management and economically optimized allocation of the valuable water resources and their protection from pollution. A recent study by Deutsche Bank Research indicated that already today 5 out of the 10 most attractive markets for water technology investment in the world are located in the Circum-Mediterranean region, yet these are the regions most prone to experiencing severe and increasing water scarcity due to climate change.

The diversity and complexity of the water problems in the Circum-Mediterranean area call for a clear and focused research program in order to successfully meet the imminent challenges and to direct the ongoing developments towards socio-economic and ecological sustainability. We have therefore identified and prioritized four fields of research:

Catchment-scale water management studies

A prerequisite for all catchment-scale water management studies is a reliable quantification of the resources and their present and future availability from different sources. This requires the integration of all existing data and information, the evaluation of data gaps, the assessment of uncertainties in areas of sparse data, and also the design of field monitoring campaigns, including high-precision water balances which can indicate what the “safe yield” is in a given catchment. The analysis of the available water resources needs to include natural input into the system as well as “artificial” inputs to groundwater (artificial recharge, rainwater harvesting), surface water storage and desalinated seawater. In the Circum-Mediterranean region, only very few high quality catchment-scale studies exist which can be used as a basis for the quantitative evaluation of the existing water resources. However, to our knowledge, none of the existing studies has made projections for a time period of 50-100 years into the future, including detailed climate scenarios and incorporating anticipated future water demands. We believe that a set of representative catchments from various regions around the Mediterranean basin is needed to develop, test and demonstrate a new long-term, scenario based dynamic water management study approach and to develop guidelines for its practical implementation. In order to be able to cross reference different processes and dynamics, the observatories should exhibit all aspects of human impact (e.g. urban areas, agriculture, industry, recreation), and be of significant scale (several hundreds of km^2). Studies should include hydrologic aspects (water balance, ecology/water quality, climate etc.) as well as land use, vulnerability and economic studies. Special emphasis will need to be placed on the study and modeling of fractured and karstified aquifer systems that constitute the prime groundwater source in many Mediterranean areas. With their potentially high permeability and low storage capacity, they are especially vulnerable to changes in the water balance components, such as excessive abstraction or climate change.

We also need to link these studies to the long-term regional public and private infrastructure planning in order to demonstrate how to optimize large investment decisions in these regions. Additionally, it is not only the fresh water resources in the Circum-Mediterranean, but also the effects of the socio-economic and climatic developments on the Mediterranean basin and its ecosystem services that are a major factor influencing economic wealth in this region (e.g. fisheries and tourism). In connection with Research Field 5 on hydrologic modeling, we propose that one of the real-world test scenarios of the claimed benchmarking initiative should be applied to a Mediterranean catchment, in order to test the ability of the models to realistically represent arid conditions, and at the same time to improve predictions for the Mediterranean in order to create a basis for decision support and management.

Some key research questions to be resolved in this field are:

- How can we assess the available water resources in semi-arid and arid catchments of the Circum-Med region (e.g. aquifer characterization techniques, remote sensing, etc.) and what is the expected development in a 50-100 year perspective considering the application of novel technologies and management strategies?
- How can we reliably predict the development of available water resources for the next 50-100 years given the important disparity among climate models for the Mediterranean region and the problems of downscaling extreme precipitation events, which significantly contribute to the overall precipitation sum?
- How can we deal with the existing data scarcity?
- What are adequate concepts to face the large-scale water quantity and quality problems existent and expected in the Mediterranean area (on land) and in the Mediterranean Basin? Are there critical thresholds in respect to the spatiotemporal extent of temporary water bodies? How to prioritize management strategies for the Circum-Mediterranean area?
- How can a sustainable water management approach be integrated into regional planning, which is based on the unlimited supply of solar energy? Can we apply an approach “beyond IWRM” in this region, integrating the management of landscapes and resources (see Research Field 2)?
- How can we assure reliable infrastructure planning and sustainable management of water resources in the Mediterranean basin as whole, i.e. across national borders?
- Is the large-scale desalination of saltwater a sustainable alternative?
- Can this North African – South European case serve as a model for a combined sustainable water and energy management?

Development of innovative water-saving and water-efficient technologies

Together with the catchment-scale water management studies, the analysis of the water demand and its projected development in various sectors, and the potential for innovative water-saving and water-efficient technologies need to be specifically addressed, including the reuse of waste water, groundwater recharge techniques, rainwater harvesting and membrane design for efficient purification and/or desalination as well as efficient technologies for agricultural irrigation. In the context of waste water reuse, specific focus should be put on water quality aspects. Also, losses in distribution systems should be looked into and solutions should be developed with specific consideration of arid conditions. First priority should be given to the agricultural sector, second priority to the industrial manufacturing and the private supply sector. In cooperation with technology developers region specific technology road maps should be defined. These can be subsequently used as a basis for private and public R&D investments.

On the water demand side the following research questions should be considered:

- What is the anticipated development of water demand in view of the economic and demographic development in some representative Circum-Mediterranean catchments/basins?
- How can science - industry - decision-maker partnerships contribute to reliably solving problems related to water efficiency and water quality issues in these representative catchments?

Region-specific tools for an optimal resource allocation and distribution

In cooperation with the global change and governance studies described in the two research fields on Water Management (Research Field 2) and Governance issues (Research Field 1), region-specific tools and mechanisms for an optimal resource allocation need to be developed, including political instruments, concepts for fair water pricing, and capacity development. The specific challenge in the Circum-Mediterranean region is the implementation of an IWRM type approach, adapted to semi-arid and arid conditions with a focus on subsurface resources and water-saving, together with the selection of an efficient and realistic set of recommendations for better governance. In the light of the expected decrease in groundwater recharge, specific emphasis needs to be given to new storage concepts as well as the transport of water from one region to another in form of virtual or real water. As the Mediterranean is a very diverse region with respect to cultural backgrounds, specific social and political/institutional studies are needed as a basis for the adequate choice of measures and strategies to implement water management concepts. The questions of the transferability of concepts from one Mediterranean region to another and the region-specific obstacles to the implementation of sustainable water management plans are yet to be solved.

With respect to water management and governance in the Circum-Mediterranean region the following research aspects are crucial:

- What are the conditions and region-specific tools for a sustainable water allocation in the Circum-Mediterranean?
- What are realistic options for managing physical water scarcity in this region?
- What are the main obstacles (e.g. diverging interests) to adaptation and overcoming water scarcity?

Interlinking water supply and renewable energy production through smart grid connections

Countries in arid zones experience usually both plenty of solar energy and limited water resources. Especially the North African countries have the opportunity to achieve long-term energy independency and self-sufficiency based on solar energy. Several projects are currently exploring the potential for the MENA-countries (Middle East and North Africa) to provide electricity from solar energy production to their European neighbors, e.g. through high-voltage direct current (HVDC) electricity “highways”. Examples are the Mediterranean Solar Ring, the “Desertec” as well as the “TransGreen” projects (e.g. see http://www.desertec.org/). The introduction of such a process shall drastically transform the economies in these countries, creating new income and also leading to some significant structural changes. Research is needed to identify the potential to interlink water supply and renewable energy production and predict the anticipated long-term effects. The expected long-term increase in water scarcity in these countries paired with rising incomes will necessitate and enable these countries to replace the water intensive agricultural mass products by water-efficient cash-crops. A successful implementation of large-scale solar thermal power production would provide an opportunity to the joint production of clean water through seawater desalination and/or multi-stage distillation / waste water treatment and reuse. Research directed to the implementation of the water-energy-nexus at the large scale in an integrated Mediterranean water-energy network needs to be complemented by a scenario for decentralized energy production and desalination of water. A comparison of both an interconnected network with a centralized production of energy as well as a decentralized approach will enable us to identify benefits and disadvantages for both options, and will allow us to develop a coherent concept for a joint water and energy management in this area.

Regarding development options and linking water to other sectors, we should find answers to the following research questions:

- What are the necessary technical, economic, and institutional pre-conditions for making cooperation and trade possible and introducing cross-border water and energy supply across the Circum-Mediterranean region?
- What are the advantages and disadvantages of a centralized / decentralized approach?
- What are the necessary steps to kick-start the process and to create a critical momentum to join forces with the relevant stakeholders in the region itself?
- What are the necessary steps and applicable concepts to be taken by science, industry and public policy to provide for a sustainable future in the Circum-Mediterranean Area and its neighboring countries in terms of water management, technological progress and regional cooperation?

Annex

White Paper preparatory committee & contributing authors

Preparatory committee (contributing organizations)

BfG: Federal Freshwater Institute
BGR: Federal Institute for Geosciences and Natural Resources
BMBF: Federal Ministry of Education and Research
BMU: Federal Ministry for the Environment, Nuclear Safety and Nature Protection
Bonn University
DFG-KOWA: German Research Foundation, Senate Commission on Water
FgHW: National Association of Hydrologists
FH-DGG: National Association of Hydrogeologists
GWP: German Water Partnership
IAH: International Association of Hydrologists
IAHS: International Association of Hydrological Sciences
IfW: Institute for the Global Economy
IGB: Leibniz-Institute of Freshwater Ecology and Inland Fisheries
IHP: International Hydrological Programme
IWRM-Network Project
GWSP: Global Water Systems Project
LMU: Ludwigs-Maximilian-University Munich
NKGCF: National Committee on Global Change Research
UBA: Federal Environment Agency
UFZ: Helmholtz Centre for Environmental Research
UNU EHS: United Nations University
TERENO: Terrestrial Environmental Observatories
TU Dresden: Dresden University of Technology
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