

# **Economic assessment of risk associated with low flows in the Elbe River Basin: an integrated economic-hydrologic modelling approach**

Malte Grossmann<sup>1</sup>, Nele Lienhoop<sup>2</sup>, Stefan Vögele<sup>3</sup>, Konar Mutafoglu<sup>1</sup>, Hagen Koch<sup>4</sup>, Michael Kaltofen<sup>5</sup>, Ottfried Dietrich<sup>6</sup>

*1 Institut für Landschaftsarchitektur und Umweltplanung, Technische Universität Berlin, EB 4-2, Straße des 17. Juni 145, 10623 Berlin*

Phone: +49(0)30-31473492

Email: [grossmann@imup.tu-berlin.de](mailto:grossmann@imup.tu-berlin.de)

*2 Helmholtz Zentrum für Umweltforschung (UFZ), Department Ökonomie, Leipzig*

*3 Forschungszentrum Jülich, Institut für Energieforschung, Jülich*

*4 Brandenburgische Technische Universität (BTU), Cottbus.*

*5 DHI-WASY GmbH, Berlin*

*6 Zentrum für Agrarlandschaftsforschung (ZALF), Müncheberg*

Abstract

This paper presents a method and application to incorporate an economic valuation approach into a river basin model to analyse water scarcity. It is the first integrated large scale economic-hydrologic river basin model to be presented for Germany that addresses issues of water quantity. A key methodological advance is the development of demand and economic valuation functions for water uses in the Elbe Basin. A further innovative element is the effort that has been made to include the value of recreational and environmental water uses in the assessment. These uses typically have high economic value in developed economies but are often neglected due to methodological problems associated with their valuation. Second, this paper presents the application of this model to assess in economic terms the potential effects of climate induced changes in water availability on the main water uses within the Elbe Basin. Hydropower plants, sub-irrigated wetlands, sprinkler irrigation and instream flow demand for recreation use of waterways, and to some further extent industrial water uses and pond fisheries are the major affected water uses both under current and future conditions in the German part of the basin. According to this analysis it is therefore the increased water demand resulting from increased evapo-transpiration demands of agricultural crops and wetlands and the instream uses that are sensitive to variation in flows that are to be expected to be most at risk from climate change in the basin. The results show that losses are only observed at less than 50 % of the demand sites and less than 20 % of the considered demand sites are responsible for the largest share of total losses. Exceptions are hydropower plants and wetlands, of which nearly all sites are affected by changes in water availability. A further result is that the effects of reduced water availability will tend to exacerbate existing shortages rather than induce losses at hitherto unaffected demand sites. This is interesting, as it implies that management attention may be focused on already

observable water management problems and that is not to be expected that major new hotspots will develop.

*Keywords: integrated economic-hydrologic model, water use, climate change, economic assessment*

## Introduction

The Elbe Basin, which has a catchment area of ca. 148 268 km<sup>2</sup>, is one of the European basins that to date experiences water scarcity and recurrent low flows during summer months. The main reason for this is the low yearly precipitation total of ca. 616 mm in the period from 1951-2000. Recent climate change is characterised by two trends: increasing mean annual temperatures and a decrease of total precipitation including a shift towards increased winter precipitation. A continuation of this trend in the central part of the Elbe is therefore mostly likely to aggravate the existing water scarcity in parts of the basin. There is increasing information on the potential magnitude of climate change and climate variability available (Gerstengarbe et al. 2008, Zebisch et al. 2005). Climate change is only one of the pressures facing the hydrological system and water resources. Other regional change such as economic and population development with associated land use changes also have a profound impact on the hydrological cycle that may both relieve or increase the pressure on the water resource system. The Elbe has a transboundary river basin: approximately two thirds of the catchments area is in Germany and one third in the Czech Republic. The largest share of the German basin is located in the eastern German states, so that taken together with the Czech part the economy of the basin is strongly influenced by post-socialist transformation processes. Reduced population growth and economic and technological catch up processes have lead to significant reductions in industrial and domestic water demand that may be expected to reduce the pressure on the water resource system well into the future. The demise of open cast lignite mining, on the other side, has accentuated water shortages in several regions of the basin, because pumping of groundwater has ceased and additional water is now required for restoration of the mines. At the same time recreational and environmental demands for water are becoming more important. For example the recreational use of waterways has become of increasing importance with the development of the tourism industry. The conservation of fen wetlands, that constitute large parts of the lowland basin and have been intensively drained for agricultural purposes, also requires additional water for their restoration and maintenance of water levels.

It is more or less consensus that it is not only necessary to mitigate climate change by reducing greenhouse gases but also to adapt to the inevitability of climate change by reducing vulnerability to its impacts. As water scarcity increases, methods based on fixed water requirements and yields are proving inadequate to address the multitude of possible adaptation options. Economic valuation provides a consistent and understandable principle to help evaluate complex mixes of infrastructure and policy options that increase water supplies, reduce water demand and reallocate water use rights.

This paper presents a method and application to incorporate an economic valuation approach into a river basin model to analyse water scarcity. Because water scarcity is not an issue in most German river basins with the exception of the Elbe, to date no integrated economic-hydrologic model incorporating all major uses for a large basin has been developed. A key methodological innovation

reported in this paper is therefore the development of demand and economic valuation functions for water uses in the Elbe Basin and their integration into an existing water resource modelling framework: WBalMo (Kaden et al. 2005). Initial efforts to include economic valuation functions were made for the Spree-Schwarze Elster sub-basin of the Elbe (Kaltofen et al. 2004, Messner et al. 2007, Grossmann 2005). This current study presents an expansion of these efforts. It is the first integrated large scale economic-hydrologic river basin model to be presented for Germany that addresses issues of water quantity. Whereas to date water use processes were predominantly incorporated into the WBalMo as fixed time dependant planning values, a more dynamic description of the use process (water demand and return flows) was developed and integrated into the WBalMo Elbe model. A further innovative element is the effort that has been made to include the value of recreational and environmental water uses in the assessment. These uses typically have high economic value in developed economies but are often neglected due to methodological problems associated with their valuation.

Second, this paper presents the application of this model to assess in economic terms the potential effects of climate induced changes in water availability on the main water uses within the Elbe Basin. The aggravating or relieving effects of changes in water demand that may result from socio-economic change are taken into account. In a further paper adaptation options will be explored.

The remainder of this paper is organised as follows: the section on methods generally describes some key methodological aspects of our approach. After a short review of approaches to integrated economic – hydrologic models, our stochastic simulation approach is outlined. Then the concepts of risk, coping range and adaptation are introduced. This is followed by a general description of our approach to the economic valuation of water uses and cost benefit analysis. A short overview of the scenarios and database completes this section. The main body of this paper describes the specific demand and loss functions we developed for the water uses in detail, as these have not been documented elsewhere. Finally some selected results regarding water use, water scarcity and effects of climate change on water uses and basins are presented and discussed with regard to their implications for water management and model development.

## **Method**

### **Integrated economic and hydrologic models: a short review**

Combined hydrologic and economic models are best equipped to assess water management and policy issues at the river basin level (Young 1995). However many challenges to integrated modelling of economic and hydrologic components remain. Despite the critical importance of economic variables in water resource management, most studies have generally been dominated by water resource planning from an engineering point of view. At the same time, economic or policy analysis studies have usually focused solely on profit maximisation of water uses for irrigation, industrial, hydropower or domestic purposes and have tended to ignore instream water uses for recreation and environmental purposes such as water quality and maintenance of wetland ecosystems. Only within the last two decades, with the advent of the concept of Integrated Water Resources Management and the advance of computer technology have integrated approaches to river basin modelling at a large scale been developed. The two principal approaches are simulation – to simulate water resources behaviour

based on set of rules governing water allocation and infrastructure operation and optimisation – to optimise allocation based on an objective function and accompanying constraints. McKinney et al (1999) provide an overview on water resources modelling at the river basin scale based on the optimisation – simulation classification. According to these authors, simulation and optimisation models of basin scale water resource systems are complementary research tools to address problems related to the competition over scarce water resources and the design of alternative systems of water allocation. The basic data requirements and understanding of systems operation are similar. All approaches require the construction of benefit or loss functions to describe the economic value of the water uses considered. The strength of the optimisation models lies in the ability to identify economically efficient water allocations and to analyse different institutional mechanisms of water resources management and water allocation. The more detailed analysis of the hydrological processes made possible with simulation models enables an assessment of the feasibility of management options with regard to infrastructure operations and to identify systems components that have a high risk of failure under extreme conditions.

Basically three major problem settings have motivated the development of basin wide integrated water resources models: (a) to develop strategies to address drought and periodic water shortages (b) to assess basin wide efficiency of water use and to assess instruments to improve efficiency for example by inter-sectoral reallocations in water scarce basins and (c) to assess infrastructure investments in terms of benefits and costs in the context of long term water systems planning. Whereas projections of demand have always been of importance to long term planning, it is only recently that the effects of climate change on the water supply have come into focus.

A good example of the first type of application is the series of models developed for the Colorado River (Booker 1995, Booker and Young 1994, Booker and Colby 1995 Ward et al. 2006). These models use nonlinear optimisation for the analysis of the performance of alternative institutional mechanisms for water resource allocation in the Colorado River Basin based on economic benefit functions. The authors examine the effects of alternative policy responses to drought under the objective of minimising economic damages resulting from drought. Policy response analyzed include (1) maximum water storage in the basin to reduce evaporative losses; (2) maintaining of hydropower capability (3) shift to proportional sharing of shortfalls (4) shifts of shortfalls to agriculture, the largest consumptive water user (5) adoption of intrastate market and interstate market allocation mechanisms.

A second set of models goes back to irrigation planning and the question of competition between irrigation and other water uses under conditions of water scarcity. The approach is also based on an optimisation approach and evaluates economic benefit of water use for different water management instruments based on production and benefit functions with respect to major water uses. An early example is the model of the Indus Basin for irrigation planning with environmental considerations (Ahmad and Kutcher 1992). Cai et al. (2003) developed hydrology inferred policy analysis tools for water allocation decisions in the Aral Sea Basin. This modelling concept has subsequently been developed and applied for a series of large river basins including the Maipo (Rosegrant et al. 2000), Mekong (Ringler 2001), Volta (Obeng-Asiedu, 2004). The focus of all these models is to analyse competition between agricultural, urban, industrial and environmental water uses and to explore the potentials to increase the efficiency of water use. The instruments analysed include (1) different formulation of water rights (2) demand management instruments including tradeable water rights (3) intra basin

transfers (4) increase in reservoir capacity and operation. To some extent these models also attempt to address benefits of environmental water demands, for example of wetlands (Ringler and Cai 2006).

The model approach developed for California (Tanaka et al. 2006, Jenkins et al. 2003 and Draper et al. 2002) is an example for the application of an integrated economic hydrologic approach to assess the long term adaptive capacity of a water resource system in economic terms. The network flow based optimisation approach minimises the economic operating and scarcity costs of water supply subject to water balance, capacity and environmental constraints. In order to describe scarcity costs, loss functions were developed for the major water uses. The loss functions are not only used within the optimisation framework, but also for post processing of simulation results. The modelling approach is used to illustrate how the infrastructure and water management might adapt in an economically optimal way to changes in climate in the context of higher future populations and changes in land use and technology. Available climate change responses that are analysed include (1) additional water supply capacities such as surface reservoirs, groundwater recharge, water transfers and waste water reuse (2) changes in water systems operation such as seasonal variations in management, conjunctive use, groundwater banking, improved reservoir operation (3) changes in water allocation rules including market mechanisms, changes in water rights and pricing schedules (4) improvement of water use efficiency in urban and agricultural water uses.

### **Stochastic simulation of long-term water availability and management**

We use a simulation model to analyse effects of changes in water availability and water demand within the Elbe Basin. This modelling framework, named WBalMo, has been developed to address long term water resource planning under conditions of water scarcity. It allows to model very large river basins over 100.000 km<sup>2</sup> (Kaden et al. 2005) and has been adapted to the conditions of the Elbe Basin as the WBalMo Elbe (Kaltofen et al. 2008). The simulation of the natural discharge and climate parameters follows a stochastic approach, whereby these input parameters are provided by a stochastic simulation of runoff conditions. Water use processes are considered to be deterministic and dependant on changes with time and meteorological conditions. The model describes the flow of the river system as a node link network. It is subdivided into major sub-basins that total 22 for the Elbe. Key model elements are the balance profiles (BP), set along the watercourses, the catchments (CM), water users (WU) and reservoirs (R) and wetlands (WET). Water management rules not covered by standard model features are programmed within so called dynamic elements (DYN). The model operates on a monthly time step and balances water demand and water supply according to the physical capacities of the river and water management infrastructure and the water management rules in place. Water is allocated not only on a first come first serve basis, but according to the rank or priority accorded to a water use within the system of water use rights. Within the WBalMo Elbe setup, the simulation of the water balance is carried out with 100 stochastically generated realisations of the climatic and discharge conditions over a period of 50 years. This procedure enables the estimation of water supply reliabilities by means of statistical analysis after completion of the simulation.

### Some key concepts: risk, coping range and adaptive capacity

We utilise the stochastic simulation framework to develop a risk approach to assess effects of low flows or drought conditions on water users. A key aspect of this approach is the clear distinction between two factors that determine the risk to a particular system, the hazard, which is “a potentially damaging physical event .....[that] is characterised by its location, intensity, frequency and probability” and the vulnerability that is composed of the exposition (location) and sensitivity or susceptibility, which denotes the “relationship between the severity of hazard and the degree of damage caused” (UN 2004). The sensitivity or susceptibility relationship is commonly termed damage or loss function in the engineering and economics literature. A loss function is a function that maps an event onto a real number representing economic cost associated with the event. Loss functions in economics are typically expressed in monetary terms. Risk is defined in this context as the “expected losses due to a particular hazard for a given area and reference period” (Adams, 1995). The loss function is expressed as a function of a random distributed variable: water availability as modelled in the stochastic simulation of the water system. As a result we can establish a cumulative distribution function and an expected value. The expected annual loss, also known as risk, is then defined as:

$$aL = \int_{-\infty}^{\infty} \lambda(x) f(x) dx$$

where  $\lambda(x)$  is the loss function,  $x$  is a continuous random variable describing water availability,  $f(x)$  is the probability density function.

We implement this approach by calculating risk from a discrete number of realisations ( $n=100$ ) for a time period of five years as follows:

$$aL_{p,ds} = \sum_{i=1}^{100} P_i L_{i,ds}$$

where  $aL$  is the expectation value or average annual loss in a year of period  $p$  at demand site  $ds$ ,  $i$  is the realisation with probability  $P_i$  and loss  $L_{i,ds}$  is the loss at demand site  $ds$  in realisation  $i$ .

This basic approach is implemented for every water user. The average annual loss may be aggregated, depending on analytical interest, to economic sectors or river basin districts.

Consistent throughout the literature is further the notion that what we define as vulnerability or risk, is not only reflective of the exposure and sensitivity of the system to hazardous conditions but also the ability or capacity to cope, adapt or recover from the effects of those conditions (Aerts and Droogers 2004, Smit and Wandel 2006). Adaptations are manifestations of adaptive capacity and they represent ways of reducing exposure or susceptibility and thus risk. Clearly there are many forms and levels of adaptation and these may be classified in many different ways including by timing (anticipatory or reactive), intent (autonomous or planned), scope (local or widespread) and form (technological, behavioural, institutional, etc.) (Smit and Wandel 2006). Adaptive capacity has been analysed in various ways, including via the concept of coping ranges (Smit and Pilifosova 2003). Most water uses can cope with normal climatic conditions and moderate deviations from the norm, but exposures involving extreme events may lie outside

the coping range. Like some other authors, we use the term coping range to denote the shorter term capacity to deal with droughts and employ the term adaptive capacity to denote longer term adjustments. This distinction is relevant for the type of analysis that can be carried out with the WBalMo model, because many short term coping mechanisms, even when associated with additional costs, are included in the definition of the loss functions and formulation of the current water management rules within the model. The coping range can increase or decrease with time. External socio-economic factors may lead to a narrower or wider coping range, for example because the water use intensity of water demanding production processes decreases. Furthermore, the cumulative effects of increased frequency of events near the limit of the coping range may decrease the coping range or lead to the abandonment of a certain water use altogether. Such feedback effects are not considered in the model setup. Adaptive adjustments on the other hand are not modelled endogenously, but are analysed as different management or adaptation scenarios, that include changes to the water allocation rules, investments in the water supply infrastructure or major changes in the water demanding use processes. The focus of this paper is on the analysis of low flows taking available coping mechanisms into account, whereas further papers will explore adaptive measures to water management (Lienhoop et al. 2008).

### **Estimation and valuation of water use**

In contrary to most integrated economic-hydrologic modelling approaches, with some notable exceptions (Jenkins et al. 2003), we use economic loss functions instead of benefit functions. Loss functions are essentially complementary to utility functions that represent benefit. One of the methodological advantages is that estimates of losses are easier to be made than estimates of benefit under conditions of data scarcity. A disadvantage is that reference has to be made to a maximum or target water demand level. In doing so, we define zero losses as occurring at the forecasted level of demand (maximum or target demand).

In order to derive loss functions, at first maximum water demand is defined as the amount current users would require if water were priced at its current level and had unrestricted availability. In any period in which deliveries are less than the maximum demanded by users, economic losses represent the economic value or benefits that users would gain from additional water if deliveries were increased to the maximum quantity demanded. Losses therefore reflect the total value of the forgone water use.

Particular care is needed in understanding what precisely is meant by water use. Conventional terminology distinguishes between off stream and in stream uses. Off stream are those requiring withdrawals or diversion from a surface water source. Several factors are involved in measuring the amount of water “used” in an off-stream activity. Withdrawal refers to the amount of water diverted or pumped from the source of supply. With consumptive use, water is no longer available because it has been evaporated, transpired, incorporated into products or otherwise removed from the hydrological system. Return flow is the amount that of water that is returned to the water system from the point of use and thus becomes available for further use. Generally speaking consumptive use plus return flows sums to withdrawal. Withdrawal and consumption are the two principal concepts by which water use is measured. The loss functions refer to the loss incurred from the water deficit, which is the difference between demanded and actual withdrawal.

The modules that were developed and integrated into the WBalMo model for each water use consist of three interrelated subroutines. The first step calculates the water demand for each month. These routines combine the long-term trend projections generated with models or scenarios exogenous to WBalMo and modify this demand in relation to the specific climatic parameters for the simulation month. The water demand of irrigation is for example dependent on the long term trend in the irrigated area. On the short term, irrigation water demand is calculated from crop water requirements. Similarly water demand for thermal power plants is in the long term conditional on reinvestment cycles for power blocks. In the short run, water demand is dependent on the demand for cooling, which is a function of air and water temperature.

The second components are simplified models of the actual production process or utilisation pattern, which take the water availability as allocated by the water management rules for a specific month as an input. Examples are the calculation of the available pond area for aquaculture, the thermal and hydropower electricity generation or the crop yield of irrigated areas.

The third component is the actual economic valuation of the change in production or use rates that result from a reduced water availability. Principally several methods are available for estimating economic loss (Young 2005). One possibility to distinguishing water valuation methods is to classify the goods and services yielded by water as either public or private. Private goods can be further classified into producer (water is used to produce other goods or services) and consumers goods (water provided goods or services which can be directly used by consumers). Most off-stream uses of water – such as agriculture, industry or households are private goods. In contrast to private goods and services the other main type of benefit are public good benefits, which are characterised by the fact that the consumption of services yielded by water by one individual do not diminish the availability of the service to others.

Recreational uses of lakes and waterways, the protection of water dependant habitats in wetlands or flood risk reduction are typical examples of public goods. Even though there is no rivalry in the use of the services, the “production” of these public good services often is in competition with other water uses. Although there is some overlap, the valuation methods appropriate for private goods differ from those for public goods. Inductive methods are the methods most often applied to public environmental goods and have been applied for this purpose in this analysis. Inductive techniques usually employ statistical or econometrical methods to infer generalisations from individual observations. We employed contingent valuation, choice experiments and travel cost analysis to generate loss functions for recreational water uses. The details of the application of these methods are described elsewhere (Lienhop & Messner in prep, Meyerhoff & Grossmann, 2007, Grossmann 2005).

Deductive methods on the other hand are most useful for valuing water in its production use. Deductive methods employ constructed models comprising a set of behavioural postulates e. g. profit maximisation. We use the change in net income method to define loss functions for hydropower, fisheries, industry, thermal power plants, irrigation, water supply utilities and boating tourism enterprises. This method defines the increment in net producer income associated with adding or subtracting water to a production process as willingness to pay for the incremental water. Assuming that the factor prices and product prices are unaffected by the change in water availability, the change in net income associated with a discrete change in water supply is:

$$\Delta I = ((p * y_1) - (cv * x_1) - cf) - ((p * y_0) - (cv * x_0) - cf)$$

where p is the product price of product y, cv are the costs associated with variable inputs x and cf are the fixed costs. Subscript 0 and 1 denote yield and variable inputs without and with changes in water supply.

A further important distinction for our analysis is that between short- and long run values. This distinction relates to the degree of fixity of certain inputs, particularly where water is a producer good, as in crop irrigation, industry or power generation. In the short run, where some inputs associated with water use are fixed, estimates of the capacity is fixed, estimates of changes in the net value of output can appropriately ignore the sunk costs of the fixed resources. However in the long run all costs must be covered. For purposes of water planning, a short run formulation is appropriate for modelling temporary variations in water supply. For the analysis of adaptation options that may include long-lived capital investments, all costs must be considered. We use a short run approach for the formulation of the loss functions to describe scarcity costs and a long run approach for the comparison of adaptation measures within a cost-benefit analysis framework.

### **Cost-benefit analysis of adaptation and water management options**

We use the average annual loss as our basic indicator to characterise water scarcity costs and the change in scarcity costs from one period to another. These costs provide an estimate of the costs of climate change.

The criterion of minimum expected loss (or minimum risk) is a widely used criterion for choosing between different management options. For the comparison of different adaptation or water management options that include changes to the level of production of a water user, the net benefits of an adaptation option accruing to water users can be summarised as follows:

$$B = \sum_{t=0}^n (gwm_t - gwo_t - f_t - aL_t) * (1 + r)^{-t+1}$$

with B total benefit, t is a year during the schemes life, n expected life of the scheme, gwm is expected gross margin in year t with adaptation measure in place, gwo is the gross margin without the adaptation measure, aL is the expected annual loss and f is the net change in fixed costs associated with the adaptation measure and r is the discount rate. This formula yields the capital sum to be weighed against the investment costs, without allowances for subsidies within either costs or benefits.

For the comparison of different adaptation or management options in a least cost planning framework, total costs (TC) are compared as the summation of expected annual loss (aL) of all users over all years (t) plus the expected total costs (C) for water management measures (for example costs of water transfers) after discounting:

$$TC = \sum_t \sum_{ds} aL * (1 + r)^{-t+1} + \sum_t \sum_{measure} C * (1 + r)^{-t+1}$$

subject to the restriction that minimum flow requirements (above all, but not limited to environmental minimum flows) be secured.

Currently we consider adaptation options that increase water supply by inter-basin water transfer and changes in the water level management of wetlands. We do not yet consider demand side options, such as investments in technological changes, even though the model is in principle capable to do so. The results of the adaptation measures are reported in a further paper.

### Scenario analysis

The effects of climate change are analysed on the basis of a set of scenarios, which have been developed for the Elbe (Hartje et al. 2008, Gerstengarbe et al 2008). These scenarios include both the effects of climate and land use changes on water availability and the changes in the water demand of major users that are determined by socio-economic change. Within this paper two baseline scenarios are compared, Basis A1° STAR T2 and Basis B2+ STAR T2. The A1 baseline assumes higher economic growth rates than the B2 scenario. A further key difference is the orientation of environmental policy, especially energy policy. In the + scenario, more ambitious reduction targets for CO2 are set, that results in relative higher prices for CO2 emission certificates. As a result lignite mining is faded out. In the ° scenario, less ambitious reduction targets are assumed and as a result lignite coal mining is continued. The STAR T2 scenario corresponds to an average increase of temperature of 2° C for the Elbe estuary and 2,8°C for the middle and upper Elbe until 2050. For the baseline scenarios it is assumed that water management corresponds to the current management practice. For both these scenarios additional climatic variance has been analysed, by selecting also a dryer (t) and a wetter (f) projection of the climate scenario: STAR T2t and STAR T2f (cf. Gerstengarbe et al 2008).

### Overview over the water users and data basis

The WBalMo Elbe model is developed on the basis of different data sources in different parts of the basin. Water users to be included in the Elbe model were determined on the basis of two criteria: they were major water users with regard to their total water demand or their water use was assumed to be associated with a high economic value. The intention was to cover all major instream and offstream water uses. Instream water uses included to date are hydropower generation and recreational use of inland waterways. Off stream uses include water demand for industry, public water supply utilities, thermal power plants, restoration of mining pits, sprinkler irrigation of agricultural crops and sub-irrigation of wetland sites that are mainly used as agricultural grassland. Table 1 summarises the current total number of water users included in the model and the number of demand sites that currently have a dynamic demand and a loss function. As the database of the model is extended, a more homogeneous coverage of the German and Czech Elbe Basin for all users is intended. Because of this we report water use for the whole Elbe river system but limit our economic assessment of low flows to the German part of the basin. Data describing the locality and estimates of current water use or current allocated water rights were provided by the different state and local water management authorities. All other user specific data that is required such as irrigated area, pond area or installed power plant capacity were subsequently compiled by the authors from various sources specifically for this study.

	Total demand sites		Demand sites with a loss function	
	Cz	D	Cz	D
Pond fisheries	1	59	*	49

Industry	30	78	*	39
Thermal power plants	17	25	*	15
Irrigation	15	86	*	77
Locks on waterways	*	25	*	17
Hydropower	*	50	*	49
Public water supply utilities	34	94	*	20
Wetlands	0	35	*	35
Restoration of lignite mining pits	*	19	*	19

\* missing to date because of lacking data

Table 1: Number of water users by sector included in the WBaIMo Elbe for the Czech (CZ and German (D) sub-basins.

## Demand and loss functions for major water uses

In the following section the approach chosen to model water demand and economic losses within the framework of the integrated economic hydrologic model are described in detail for each sector. Key characteristics of the selected water users in relation to the whole sectors are described, before the demand and loss functions are presented. In addition an attempt is made to clarify the key input parameters that are varied in the context of the scenario analysis and the main coping and adaptation options that have been implemented in the formulation of the functions to date. DQ, SQ and RQ generally denote demand for withdrawal or through flow, actual withdrawal or through flow and return flows. General subscripts used are ds, m and t: ds is a specific demand site, t denotes a specific year, and m a month of the year. These subscripts indicate the spatial and temporal resolution for the variables and parameters required by the model.

### Thermal power plants

There are several different types of thermal power plants operated in the Elbe Basin, with capacities ranging from a few kW to several GW. Different fuels are used that include nuclear, gas and lignite coal. Whilst some power plants are operated to produce base load electricity throughout the year, others are mainly operated to generate heating energy during the winter. Only the 25 power plants in the German section with a capacity larger than 50 MW are included as water users in the WBALMO Elbe model. This includes all major power plants upstream of the nuclear power plants on the lower Elbe. An additional 17 thermal power plants are included as water users for the Czech part of the river basin. The cooling system is one of the key determinants of water use intensity. Because of the fundamental limits to thermodynamic efficiency of any heat engine, all thermal power plants produce waste heat as a byproduct of the useful electrical energy produced. Where economically and environmentally possible, the use of cooling water from a river instead of a cooling tower is preferred because this type of cooling can save the cost of a cooling tower and may have lower energy costs for pumping cooling water through the plant's heat exchangers. However, the waste heat can cause the temperature of the water to rise detectably and this may be a limiting factor in situations where the permissible maximum temperatures of river water may be exceeded. Of the power plants included in the WBALMO Elbe model 9 have a through flow cooling, whilst the rest have a have a cooling tower system.

### Estimation of water demand and water use

The key factors that determine water demand are the installed plant capacity and the available cooling technology. The development of the power plant capacity and technology at different sites is the output of an exogenous model of the power plant sector, which is described in detail in Vögele et al. (2008). Additional factors that limit cooling water use are the actual temperature of the river water that determines the maximum additional heat load before permissible water temperatures are reached. Air temperature and humidity are important variable that determine the amount of water evaporated in the cooling tower.

The monthly water demand of a power plant with through flow cooling can be estimated according to the following approach (LAWA, 1983):

$$DQ_{(ds,m,t)} = \frac{\Phi_{(ds,m,t)}}{\rho \cdot c \cdot AS_{(ds,m,t)}}$$

where DQ is the cooling water demand in [m<sup>3</sup>],  $\Phi$  is the heat flow that has to be conducted in [MJ],  $\rho$  is the density of water in [t/m<sup>3</sup>], c is the specific heat capacity of water in [MJ/t\*K] and AS is the permissible rise in temperature of the cooling water in [K].

The permissible rise in temperature of the cooling water is calculated as the difference of the estimated actual water temperature T in [K] and the maximal permissible temperature Tmax in [K] at a demand site:

$$AS_{(ds,m,t)} = \max(T_{\max(ds)} - T_{(ds,m,t)}; 0)$$

The demand for cooling water is thus the quotient of the heat that has to be conveyed and the capacity of water to absorb that heat. The heat that has to be conveyed is dependant on the energy efficiency of the power plant and the amount of heat that is either lost and released to the environment via other pathways such as steam production or is used for heating purposes. The heat that has to be conveyed is estimated as follows:

$$\Phi_{(ds,m,t)} = BR_{(ds,m,t)} \cdot (1 - \eta_{ges}) \cdot (1 - \alpha)$$

where BR is the fuel use in [MJ],  $\eta_{ges}$  is the efficiency of fuel use of the plant,  $\alpha$  is a correction factor to account for lost heat that does not have to be conveyed via cooling water.

The fuel use is estimated as follows:

$$BR_{(ds,m,t)} = nKW_{(ds,t)} \cdot h_{(ds,m,t)} \cdot 3,6 \cdot \frac{1}{\eta_{elek}}$$

where nKW is the nominal capacity of the power plant in [kW], h is the capacity utilisation of the power plant in [full load hours] and  $\eta_{elek}$  is the electricity energy efficiency.

The demand for water of plants with a cooling tower is the sum of the water required for evaporation in the cooling tower and the water required to keep the concentration of solubles in the water of the cooling system under the required

level. In contrast to through-flow cooling water is thus permanently taken from the river and lost through evaporation. The heat that is conveyed from a cooling tower is contingent on the air temperature and humidity. Taking the conduction of heat through the cooling tower into account, the equation for through flow cooling is extended and becomes:

$$DQ_{(ds,m,t)} = \frac{\Phi_{(ds,m,t)} \cdot (1 - \beta) \cdot \omega_{(ds,m,t)}}{\varrho \cdot c \cdot AS_{(ds,m,t)}} \cdot EZ$$

where  $\beta$  is the average share of heat that is conducted via the cooling tower,  $\omega$  is a correction factor that takes air temperature and humidity into account and EZ is the densification factor.

The value for  $\omega$  is around 0,993. The correction factor  $\omega$  is calculated on a monthly basis in order to take effects of temperature and humidity into account. The factor ranges between 0,75 (cold dry winter month) and 1,25 (hot humid summer month). The densification factor is a measure for the concentration of solubles in the cooling water system. It is calculated as:

$$EZ = \frac{SQ}{RQ}$$

and is to be maintained in a range between 1 and 3. The return flow can then be calculated as:

$$RQ_{(ds,m,t)} = \frac{SQ_{(ds,m,t)}}{EZ}$$

### Loss function

If water availability is limited or if the temperature of the discharged cooling water may not be raised further, the capacity of the power plant has to be reduced. The actual monthly production capacity of the power plant can be estimated by rearranging the water demand equation and to solve for the capacity of the plant using available water supply and permissible temperature rise as an input. For plants with through flow cooling this gives:

$$KW_{(ds,m,t)} = \frac{SQ_{(ds,m,t)} \cdot 4,2 \cdot AS_{(ds,m,t)}}{h_{(ds,m,t)} \cdot 3,6 \cdot \frac{1 - \eta_{ges}}{\eta_{elek}} \cdot (1 - \alpha)}$$

and for plants with a cooling tower:

$$KW_{(ds,m,t)} = \frac{SQ_{(ds,m,t)} \cdot 4,2 \cdot AS_{(ds,m,t)}}{h_{(ds,m,t)} \cdot 3,6 \cdot \frac{1 - \eta_{ges}}{\eta_{elek}} \cdot (1 - \alpha) \cdot (1 - \beta) \cdot \omega_{(ds,m,t)} \cdot EZ}$$

where KW is the actual capacity of the power plant in [kW], SQ is the available water in [m<sup>3</sup>], AS is the maximal permissible rise in temperature of the cooling water in [K], all others as above.

Valuation of losses in the thermal power plant sector is based on a change in net rents approach. Under the assumption that the total annual electricity demand to be supplied by the power utility is constant, it is assumed that additional electricity is bought on the electricity market to compensate a reduction of a power plants energy production. Annual loss is then calculated as the reduction in net rents by calculating the costs of the required electricity purchases, net of savings in variable costs, as follows:

$$L_{-TP_{(ds,t)}} = \sum_m (nKW_{(ds)} - KW_{(ds,m,t)}) * h * (P_{(t)} - Cv_{(ds)})$$

where nKW is the nominal capacity of the power plant in [kW], KW is the actual power production capacity in [kW], h is the capacity utilisation of the power plant in [full load hours], P is the purchasing price for electricity in [€/kwh] and Cv are the variable costs of production in [€/KWh].

### *Coping and adaptation options*

Long term adaptation options for power plants include changes in cooling technology. It is assumed that cooling towers, where these are missing, are constructed when a replacement investment for a power plant is made. This investment is determined in the exogenous model of the power sector (Vögele et al 2008). Short term coping mechanisms implemented in the model are the utilisation of the available range for raising the temperature of the cooling water. An additional coping mechanism that is implemented, but not fully explained here, is that the model will bring forward the required shut downs for maintenance to avoid losses, if a regularly scheduled maintenance is due in near future.

### *Variables for scenario analysis,*

Key variables that are varied for the scenario analysis are the exogenously determined changes in the stock of thermal power plants that result in changes in both generating capacity and cooling technology (Vögele et al. 2008). Key variable for the loss function is the market price of base load electricity. Whereas it is assumed that baseload electricity prices in the scenarios with a more stringent environmental policy (**B2+**) increase from 0,02 €/Kwh in 2000 to 0,09 €/Kwh in 2050 an increase to 0,07 €/kwh is assumed for the less stringent environmental policy (**A1°**).

### **Hydropower**

There are approximately 484 hydropower plants in the German part of the Elbe Basin. Over 400 of these have a nominal capacity which is less than 500 kW. 56 plants have a capacity ranging between 500 kW and 5 MW. 9 hydropower plants have a nominal capacity above 5 MW, three of which have a capacity above 150 MW. Plants with a capacity above 5 MW, are with one exemption, pumped hydro power plants, which use surplus energy from the power grid to pump water from a lower reservoir to a higher reservoir for a subsequent release at peak electricity demand. These plants were not included in WBALMO Elbe Model because water is used in a more or less closed cycle. Plants with a capacity below 500 kW were also not included, because these are located on small tributaries for which no flows are modelled. No data on hydro-power plants in the Czech part of the basin was available yet.

### Estimation of water demand and water use

As all reservoir release and run of river hydropower plants are producing base load electricity which is in constant demand, monthly water demand is equated to maximum turbine flow capacity:

$$DQ_{(ds,m,t)} = QT \max_{ds}$$

where DQ is water demand in [m<sup>3</sup>/s] and QTmax is the specific maximal turbine capacity in [m<sup>3</sup>/s] of the hydropower plant. Return flows are equal to inflows.

### Loss function

The monthly electricity production of a hydropower plant is a function of the mass of water through the turbines, the head to tail elevation difference, the time on-line per month, the generating efficiency of the turbine and generator. It can be estimated from the product of the flow through the turbines, the drop in elevation and a constant conversion factor. This factor is the product of the density of water  $\rho$ , the acceleration of gravity  $g$  and the turbine and generator efficiency  $\eta$  and is usually approximated with a value of 7. For reservoirs, the head is equal to the difference between the average elevation of the water level in the reservoir during a month and a constant tail water elevation. For run of river hydropower plants, the specific head is assumed to be constant. The available flow for hydropower generation is determined by the reservoir release or the flow of the river. Maximum turbine flows define the upper capacity limits. In addition, flow of the river hydropower plants that divert water from the main river, can only do so as long as minimum flow requirements are met. There are separate production functions for reservoir and flow of the river hydropower plants. Power production for flow of river hydropower plants is calculated as

$$KWh_{(ds,m,t)} = \min(SQ_{(ds,m,t)} - (MNQ_{(ds)} * rateMin_{(ds)}); QT \max_{(ds)}) * h_{(ds)} * 7 * hrs$$

and for reservoir hydropower plants as

$$KWh_{(ds,m,t)} = \min(SQ_{(ds,m,t)}; QT \max_{(ds)}) * hres_{(ds,m,t)} * 7 * hrs$$

where KWh is the annual power production in [KWh], QTmax is the maximum turbine flow capacity in [m<sup>3</sup>/s], h is the fixed water head for flow of river hydropower plants in [m], hres is the month's average head of water in the reservoir in [m], SQ is the actual flow in month m and year t, hrs are the monthly operation time in [hours], MNQ is the average low flow at a flow of river demand site [m<sup>3</sup>/s] and rateMin is the share of the MNQ that is required as minimum flow in the river bed.

Loss is defined as the difference in value of annual electricity produced at hypothetical maximal production and actual production levels. The average price of base load electricity is used to determine loss for plants not eligible for guaranteed prices under the Renewable Energy Act (EEG), whereas the guaranteed prices are assumed for eligible power plants:

$$L_{-}HP_{(ds,t)} = \sum_m (nKWh_{(ds)} - KWh_{(ds,m,t)}) * P_{(ds,t)}$$

where nKWh is the nominal energy production capacity of the hydropower plant in [KWh / month], KWh is the actual energy production in [KWh/month], P is the applicable price in [€/KWh] at a demand site.

#### *Variables for scenario analysis*

Key variables for scenario analysis are changes in base load and guaranteed electricity prices under the Renewable Energy Act. Whereas it is assumed that base load electricity prices in the scenarios with a more stringent environmental policy (**B2+**) increase from 0,02 €/KWh in 2000 to 0,09 €/KWh in 2050 an increase to 0,07 €/KWh is assumed for the less stringent environmental policy (**A1°**). Guaranteed electricity prices under the renewable energy act for plants between 0,05-5MW is assumed to be constant at 0,065 €/KWh until 2035, which would be the end of the hypothetically longest guarantee period of 15 years. Beyond this point base load prices are assumed.

#### **Industry**

Freshwater intake for industrial uses is either supplied by direct withdrawal from surface or groundwater resources or from piped sources as e. g. public water utilities. All major industrial abstractors of surface water are modelled within the WBalMo framework, including both individual firms as well as operators of industrial parks who supply industrial water users located at their site. A total of 86 industrial users are taken into consideration with respect to withdrawals and discharges into surface waters in the German part of the Elbe River Basin. As the focus is placed on the supply side of water resources, only those firms which actually are abstractors are taken into consideration when evaluating potential effects of temporal water scarcity. In connection with data availability issues this focus leads to a total of 50 industrial users. About half of these belong either to the chemical industry or are firms from the pulp and paper industry while the remaining are distributed over various manufacturing sectors as e. g. food and beverages, metals or non-energy mining and quarrying.

#### *Estimation of water demand and water use*

The current annual abstraction volumes and their monthly distribution are scaled by the annual change in demand of industrial water demand. The monthly demand then equals that month's fraction of the adjusted annual demand:

$$DQ_{(ds,m,t)} = (nQ_{(ds)} * DR_{(ds,t)}) * mFrac_{(ds,m)}$$

where DQ is the water demand in [m<sup>3</sup>], nQ is the nominal water demand in [m<sup>3</sup>], DR is the factor by which water demand differs from the nominal demand and mFrac is the month's fraction of average annual water use.

The demand site specific growth rate of water demand for each industrial water user is derived from an exogenous projection with the demand model for industrial water use, which is described in detail by Mutafoglu (2008). The effective water use ratios are assumed to be constant for the specific sectors, so that return flows are determined as:

$$RQ_{(ds,m,t)} = SQ_{(ds,m,t)} * (1 - effFrac_{(ds)})$$

where effFrac is the share of water that is lost in the production process by evaporation or inclusion in the product.

### Loss function

In order to estimate effects of water shortage on production in different industrial sub-sectors, a survey of industrial firms was conducted in relevant water intensive sectors in the Elbe River Basin. A total of 1602 firms were contacted of which a total of 292 responded (Mutafoglu 2008). Because only a few of the industrial firms have ever experienced water shortages, a series of contingent questions was posed in order to elucidate a possible functional relationship between reduction in water supply and production. More specifically, the firms were asked about the potential impacts of a one month water shortage of 7%, 15%, and 30% respectively, compared to the usual water intake during summer months. Furthermore, the firms were also requested to quantify that level of water shortage which would force the firm to stop operations completely. For simplicity reasons a linear relationship between water availability and the level of output is assumed between any two points on the respective curve, so that

$$rPR_{(ds,m,t)} = \text{if}(d_{(ds,m,t)} < T1_{(ds)}; 0; \text{if}(d_{(ds,m,t)} > T2_{(ds)}; 1; (d_{(ds,m,t)} - T1_{(ds)}) * \frac{1}{T2_{(ds)} - T1_{(ds)}}))$$

where rPR is the proportion of maximum production that can be maintained with the supplied water, d is the proportion of water demand that is supplied, T1 is the threshold above which production is not reduced and T2 is the threshold below which production ceases.

Valuation of losses in the industrial sector is based on a change in net income approach. It is based on the assumption that a reduction in production will lead to a proportional reduction in sales revenues. Practically all large industrial plants included in the model operate 24 hours per day and may not compensate reduced production during a period of water scarcity by increased production in another month. The reduction in net rents is estimated as the reduction in gross income net of the savings of variable costs related to production such as resource inputs to production. Because the industrial sectors produce a very wide range of different products, the revenue for each industrial production site was estimated using statistical data on the average revenue per employee. This information is available for sub-sectors and size classes from a regular survey of the industrial sector conducted by STABU (2007). Also available from this data source is the proportion of production related variable costs to total revenue. In addition information on the number of employees at each production site included in the WBalMo Elbe model was collected. Using this data, annual loss is defined as follows:

$$L\_IND_{(ds,t)} = \sum_m (gI_{(ds)} * E_{(ds)}) * rPR_{(ds,m,t)} - (gI_{(ds)} * E_{(ds)}) * rPR_{(ds,m,t)} * Cv_{(ds)}$$

Where gl is the sector and size class specific gross income per employee in [€/employee and month], E is number of employees at a production site, rPR is the proportion of maximum production that that can be maintained with the supplied water and Cv is the sector and size class specific share of variable costs in relation to gross income.

A total of six manufacturing sectors are differentiated within the valuation framework. These comprise chemicals, paper and pulp, metals, food and beverages, textiles, and non-energy mining and quarrying. To take structural

differences between different firm sizes into consideration, the firms are also differentiated with respect to employment size classes. Generally speaking, firms with a smaller number of employees show a larger share of fixed costs. Also of relevance for the modelling is the fact that gross output values per employee typically increase with increasing number of employees.

#### *Coping and adaptation options*

Currently internal coping options in the production process in the short-run, such as a temporarily more intense circulation of water during drought periods are implicitly included in the parameters of the sector specific loss functions, as derived from the responses of the survey respondents. Further adaptation or coping options such as procuring water from other sources or switching to other largely closed water circuits especially with respect to cooling are not considered to date. However, broad technological trends are taken into consideration when deriving scenarios of potential future water demand (Mutafoglu 2008). A short term substitution is not considered feasible without investment in necessary conveyance and storage infrastructure in most cases.

#### *Variables for scenario analysis*

Key variables that are varied for the scenario analysis are exogenously determined changes in demand rates, which are in turn dependant on the sector specific growth rates and development of water use efficiency. A description of the trends in water demand can be found in Mutafoglu (2008).

#### **Public water supply utilities and waste water treatment.**

Most water abstracted by public water supply utilities in the German part of the Elbe River Basin is taken from groundwater. Especially in the mountainous areas, surface water is taken from reservoirs specifically designated for drinking water supply purposes and transported to consumption sites via a system of large water pipelines. In the lowland regions bank filtration and groundwater sources predominate. In total there are 94 water works for the German section included in the WBALMO Elbe model that use surface water directly or from bank filtration. An additional 34 abstraction points for water works are included for the Czech part of the model. Loss functions are included for all 23 major water works that take surface water from reservoirs. Of these water works 9 are solely dependent on surface water and 14 use both reservoir- and bank filtration water sources. There are approximately 74 further water works that only take bank filtration water included in the model, but no loss function was included for these demand sites. Water abstracted for public water supply returns to the river at waste water treatment plants that may or may not be in the vicinity of the abstraction point. All major waste water treatment plants are included as discharges in the WBALMO Elbe model. This surmounts to a total number of 281 waste water treatment plants.

#### *Estimation of water demand and water use*

The demand site specific growth rate of water demand for each water utility is derived from an exogenous projection with the demand model for public water supply utilities, which is described in detail by Ansmann (2008). The current annual extraction rates and monthly distribution at the demand sites are scaled

by the determined annual demand increase. The monthly demand is then equal to the specific month's fraction of the adjusted annual demand:

$$DQ_{(ds,m,t)} = (nQ_{(ds)} * DR_t) * mFrac_{(m,ds)}$$

where DQ is the water demand in [m<sup>3</sup>], nQ is the nominal water demand in [m<sup>3</sup>], DR is the factor by which water demand differs from the nominal demand and mFrac is the month's fraction of average annual water use.

The return flows that occur via the waste water treatment plants were kept constant for this analysis, because the linkages between treatment plants and water abstraction sources could not yet be established. The discharge from waste water treatment plants includes water abstracted from groundwater sources and includes surface runoff in areas where surface areas are drained by the sewerage system.

### *Loss function*

Valuation of losses in the water supply utilities sector is based on a change in net income approach. In case of water scarcity we assume that bank filtration water is a substitute when surface water sources do not suffice. For those water works which do not have additional bank filtration capacity, it is assumed that water supply has to be augmented by water transported by road from adjacent water works with bank filtration. We assume that the incurring additional costs of water provisioning reduce the net income of the affected water works and annual loss is then calculated as:

$$L_{-}WW_{(ds,t)} = \sum_m (DQ_{(ds,m,t)} - SQ_{(ds,m,t)}) * (AC + TC_{(ds)})$$

where DQ and SQ are the water demand and supply in [m<sup>3</sup>], AC are the general additional costs in [€/m<sup>3</sup>] for pumping and water treatment for bank filtration and TC are the specific transport costs [€/m<sup>3</sup>] at a demand site.

Cost calculations are based on the difference between the pumping and treatment costs for surface water (0,05 – 0,06 €/m<sup>3</sup>) and bank filtration (0,075 – 0,10 €/ m<sup>3</sup>) reported by water works. Bank filtration is more expensive due to poorer water quality and higher pumping costs in comparison to water taken from drinking water reservoirs. On this basis the additional costs of procuring water from bank filtration are estimated to be roughly 0,035 €/m<sup>3</sup>. Additional costs for road transport are taken into account when there is no bank filtration water available locally. Average transport costs are estimated to be in the range of 0,03 - 0,04 €/m<sup>3</sup>.

### *Coping and adaptation options*

The endogenous coping option included in the model to date is a substitution of surface water by bank filtration water, which is in the current model version assumed to be available in unlimited amount at the surface water demand sites.

### *Variables for scenario analysis*

Key variables that are varied in the context of the scenario analysis are exogenously determined changes in demand rates, which are in turn dependant on the development of population, economic activity and water use efficiency. A description of the projected water demand for different scenarios can be found in Ansmann (2008).

## **Recreational and amenity value of recultivated mining pits in the Lusatian Lakes Region**

### *Description*

Open cast lignite mining in the region of Lusatia is one of the key factors that influence the water availability in the Spree-Havel and Schwarze-Elster sub-basins of the Elbe. The scale of the mining operations was drastically reduced as a consequence of the post socialist transformation and a landscape restoration programme was commenced. The recultivation concept foresees the creation of a new lakes district to be created by flooding the remnant mining pits. An interconnected series of 17 lakes with a total water area of 11 437 ha is being created. The major constraint with regard to the speed that the recultivation can be completed is the availability of sufficient water. Whilst three lakes have already been successfully flooded, the remaining lakes are still waiting to be flooded according to a schedule that foresees a completion around the year 2025. Investments in recreational facilities such as canals, beaches, road access, bridges and marinas have already been made and are waiting to be put to public use as soon as the water levels have risen. It is hoped that the lakes district will develop into both a recreational area for the local population and a tourism attraction that will open new chances for regional economic development in a region with high unemployment.

### *Estimation of water demand*

The demand for additional surface water for the flooding of the mining pits is estimated from the required water volume to fill each of the mining pits. In addition, the water required to compensate the annual net evaporation losses from the water surface and the balance of ground water in and outflow are taken into consideration. The maximum possible supply is subject to several constraints that include the rank of the water right in relation to other users and maximal delivery capacity of inflow infrastructure such as pipes and pumps. As long as the lakes are not filled, there are no return flows.

$$DQ_{(ds,m,t)} = (V - V_{(t-1)}) + (A_{(ds)} * (ETw_{(ds,m,t)})) + (GWi_{(ds,m,t)} - GWo_{(ds,m,t)})$$

where DQ is the remaining water demand in a month of year t in [m<sup>3</sup>], V is the volume of the mining pit that has to be filled in [m<sup>3</sup>], A is the area of the lake surface in [ha], ETw is the evaporation from a water surface in [m<sup>3</sup>/ha] and GWi and GWo are the groundwater in and outflows in [m<sup>3</sup>].

### *Loss function*

Water is supplied for recultivation purposes only once all other water demands in the river system have been satisfied. The planned flooding schedule may thus have to be prolonged, if less water than anticipated becomes available. This in turn would further postpone the completion of the lakes district and its availability for recreational purposes. A change in consumer surplus approach is chosen to value the associated disbenefits to the regional population. The parameters for the change in consumer surplus resulting from a delayed flooding were estimated from a survey (n =1500) with a contingent valuation format (cf. Lienhoop and Messner, in prep). Respondents living within a 100 km radius of the lakes region were interviewed regarding their annual willingness to pay (WTP) for the development, accessibility and upkeep of the lakes for recreational and tourism purposes. Two scenarios were presented that differed in the water area made available by 1567 ha and the WTP for both cases was asked. From the difference a marginal WTP per change in lake surface area was estimated. Respondents, that stated that they would themselves use the lakes for recreational purposes had a marginal annual WTP of 0,0016 €/ha per household and those that did not had a marginal annual WTP of 0,0009 €/ha per household. Approximately 43 % of the respondents stated that they consider themselves as users. The annual loss in consumer surplus is calculated as the difference of the total annual consumer surplus for the targeted lake area and for the actual lake area in a given year as follows:

$$L_{RLusatia}_{(ds,t)} = ((WTPu \cdot \frac{Pop_{(t)}}{HH} \cdot (1-z)) + (WTPnu \cdot \frac{Pop_{(t)}}{HH} \cdot z)) \cdot A_{(ds)} * dF_{(ds,t)}$$

Where WTPu and WTPnu are the marginal annual willingness to pay per household in [€/ha] for users and nonusers respectively, A is the total area of lake in [ha], dF is the divergence of the achieved filling state from the scheduled filling state for year a (1 if filled behind, 0 if on and -1 if before schedule), Pop is the population of the region in [persons], HH is the average household size in [persons per household] and z is the proportion of nonusers in the population.

### *Coping and adaptation options*

Adaptation mechanisms are mainly to be found in options to improve water supply, either by optimising the water management regime or by intra basin water transfers. Such management options for the Spree-Schwarze Elster sub basin have been analysed in detail and are described Koch et al. (2005 and 2006) and Lienhoop et al. (2008).

### *Variables for scenario analysis*

Key variables that are varied for the scenario analysis are exogenously determined changes in the regional population. A description of the trends in population can be found in Hoymann (2008).

## Recreational boating on inland waterways in the Spreewald Region

### *Characteristics*

The Spreewald is an inland delta of the river Spree. It is a wetland that is transected by system of rivers and canals that total more than 100 km in length in an area of ca 488 km<sup>2</sup>. These waterways are subdivided into sections whose water level is regulated by weirs. In order to allow boats to pass from on section to the next, a number of locks have been constructed, 21 of which have been included in the WBALMO Elbe model. The Spreewald is an important recreational area and is a UNESCO Biosphere Reserve. One of the main attractions is trips on traditional wooden boats, which are punted through the canals by ferryman. This activity attracts around 5 million visitors per year. About 70 % of the visitors take a short trip of about two hours and 30 % take long trips, which take between five to six hours.

### *Estimation of water demand and water use*

No specific water demand function is used for recreational boating in the Spreewald, because flows are regulated by wetland water level management and are modelled in the wetland module of the WBALMO Elbe model.

### *Loss function*

The key effect of reduced flows that is considered in the model is a disruption of the longer boating routes that require passing certain locks, because the water level in the locks is not sufficient to allow boats to pass. Monthly water levels in the locks are calculated on the basis of the wetland water tables that are an output of the wetlands module (cf. Dietrich et al. 2006 and Dietrich et al. 2008). A lock is considered impassable, when the water table is lower than the required minimal depth of approximately 0,3 m. Three major tourism and boating districts can be distinguished. A boating district is considered to be disrupted, if one of the selected key locks is impassable. The annual sum of months that boating in a district is disrupted is then calculated as follows:

$$M \lim_{(t,ds)} = \sum_m \text{if} \left( \sum_l \text{if} (nD_{(l,ds)} - dWL_{(m,t,l,ds)} \leq dm; 1; 0) > 0; 1; 0 \right)$$

where subscripts l denote locks and ds demand sites (boating district), nD is the nominal depth of water in the lock under target conditions in [m], dWL is the difference of actual water level in a month from target water level in [m] and dm is the minimum required depth in [m].

The losses that are induced by a limitation of the duration of the possible boating trips are calculated on the basis of two effects: the loss in consumer surplus of tourists and the change in net income of the ferrymen. The change in net income is calculated as the difference in price for a long and short boat trip:

$$L\_RSpreEF_{(t,ds)} = M \lim_{(ds)} * V_{(ds,t)} * \text{frac}L * dP$$

Where V is the number of monthly visitors in a boating district, fracL is the share of visitors taking a long trip and dP is the difference in price between a long and short trips in [€].

The loss of recreational value associated with a restriction of trip duration is calculated using consumer surplus derived with by an application of the travel cost method. This method estimates consumer surplus using recreational trip expenditure as a proxy for willingness to pay in estimating demand for recreational amenities (Ward 1987, Eiswerth & Englin 2000). To calculate the effect of a change in in-stream flows on the recreational value, three basic types of information are necessary: the number of visits, the recreational value of a visit, and the change in both variables under a change in navigability. An on-site survey of recreationists (n = 750) was carried out and a demand function using a zonal count-data model with a poisson regression according to Haab and McConnell (2002) was estimated. The welfare measure (consumer surplus) per trip is given by the reciprocal value of the coefficients for travel costs. We determined the recreational value to be between €5 and €6 per visit (Grossmann and Meyerhoff, in prep). To estimate the reaction of the visitors to a reduction in water availability a contingent behaviour question was included in the survey. It was asked whether respondents would still have visited the Spreewald if they had known in advance that they would not be able to take a long tour. 60% of the interviewed persons who had taken a long trip stated that they would never the less have travelled to the Spreewald. Using this information, we calculated the expected loss of recreational value by unexpected trip limitations as follows:

$$L_{RSpreewald} = M \lim_{(ds)} * V_{(ds,t)} * fracL * fracV * CS$$

Where fracV is the share of visitors that would not have come to the Spreewald, if they knew that they could only take a short trip, and CS is the consumer surplus per person and trip in [€].

#### *Coping and adaptation options*

The coping option include in the model is a shift from long trips to short trips. Other coping mechanisms, such as reduced number of persons per boat, are not considered.

#### *Variables for scenario analysis*

Key variables determining loss for scenario analysis are changes in visitation rates and prices. For the current analysis the visitation rates and prices are held constant.

### **Recreational boating on inland waterways in the Müritz Lakes Region**

The Lakes Region in the north-eastern German States of Mecklenburg Vorpommern and Brandenburg is characterised by a multitude of lakes and natural rivers which have been interconnected by artificial canals to create a network of waterways. The central Müritz Lake is connected onward to the river Elbe by the Müritz Elde Waterway to the west and to the river Havel by the Müritz-Havel-Waterway. Two important sideway extensions are the Ruppiner Gewässer and the Rheinsberger Gewässer. The Müritz Lake itself is an important reservoir, whose discharge to the waterways is regulated by weirs and influenced also by the frequency of lock use. The frequency of locking also determines the minimum flows required for maintaining navigability along the waterways. If water does not suffice, the frequency of locking has to be reduced, for example by shifting from on-demand to fixed locking schedules. The locks on the Müritz-Elde-

Waterway registered ca. 4000 boat movements and the Müritz-Havel-Waterway ca. 25 000 -30 000 boat movements per year in 2000. In total there are 18 locks on the Müritz-Elde Waterway and 27 locks on the Havel River and its tributaries above Berlin. 37 of these locks are included in the WBALMO Elbe model.

The Müritz Lakes Region is only some 130 km from Berlin, which makes it a popular destination for weekend and holiday trips. There is a long tradition of recreational boating and water sports in this region, which has become increasingly popular in the years following German reunification and the resulting accessibility for inner German tourism. The region has successfully been promoted as a holiday destination, primarily on the merits of its abundant waters. Efforts have been made to improve the conditions for recreational boating for example through the creation of marinas and the redemption of a driving licensing requirement for holiday cruisers. These factors taken together have resulted in a marked increase in the utilisation of the waterways since 1990s. The long term trend of boat movements through the locks show that activity levels on the waterways have more than doubled in the last ten years (WSA, 2006). An outcome of this increased recreational traffic is that at peak times in the summer holiday season (July – August), the capacity of the locks is exceeded and substantial waiting times of several hours have been registered. It is in this light that the authorities responsible for the upkeep and development of the waterways are discussing to increase the capacity of the locks (cf. MWB, 2001). A reduction in available water flows will on the other hand lead to increasing congestion and waiting times at locks.

#### *Estimation of water demand and water use*

The demand for water at locks is a function of the rate at which a lock operates and the specific volume of the lock. Locks may operate at regular intervals or on demand. From observed data on number of boats and the number of locking events per month for x locks and month, an empirical relationship between the number of boats passing a lock and locking events was determined, whereby the locking frequency increases with increasing number of boats and asymptotically approaches the operational maximum locking rate C<sub>max</sub>. It follows that:

$$LE_{ds,m} = ((\text{Min}((N_{ds,m,t} * \text{PAR\_A}_{ds} / \text{PAR\_B}_{ds} + N_{ds,m,t})); C_{ds} * 13 * 30)$$

Where LE is the number of locking events per month, N is the number of boats passing a specific lock, C is the maximum frequency of locking events per hour (LE/h) multiplied by the daily operating period of 13 hours and 30 days a month, PAR\_A and PAR\_B are specific parameters of the function. The monthly flow requirement DQ in [m<sup>3</sup>/s] for locking can then be determined from the volume and number of locking events plus a height dependant seepage factor of 0,005 m<sup>3</sup>/s per m as follows:

$$DQ_{ds,m} = ((LE_{ds,m} * \frac{V_{ds}}{2}) / (60 * 60 * 24 * 30)) + (0,005 * H_{ds})$$

Where V is the volume of the lock in [m<sup>3</sup>] and H is the difference in water level to be overcome [m]. The return flow is equal to the supplied flow.

### Loss function

The major effect of reduced availability of water for locking is a reduction in the number of possible locking events per month, which can be determined from rearranging the equation for water demand:

$$LE_{(ds,m,t)} = (QS_{ds,m,t} - (0,005 * H_{ds})) * (60 * 60 * 24 * 30) / V_{ds} * 2$$

A reduction in the amount of locking events will lead to increased waiting times and congestion effects especially during peak usage in summer months. Changes in waiting time result from an increase in the time span between locking events. During summer months when the system of locks is operating close to maximum capacity in addition congestion effects have to be taken into account. Queuing theory (Gross and Harris 1998) is used to calculate average waiting times. Assuming random arrival and deterministic service during the 13 daily hours of operation of the locks, the total waiting time is given as the sum of average waiting time in the queue (Tw) and average service time (Ts):

$$T_{ds,m,t} = TW_{(ds,m,t)} + TS_{(ds,m,t)} = \frac{\rho_{ds,m,t}}{2 * (1 - \rho_{ds,m,t})} * \frac{\rho_{ds,m,t}}{\lambda_{ds,m,t}} * ot + \frac{1}{\mu_{ds,m,t}}$$

and

$$\mu_{(ds,m,t)} = \frac{LE_{ds,m,t}}{30 * ot}$$

where  $\mu$  is the service rate in [locking events per hour],  $\lambda$  is the arrival rate [boats per day] and  $\rho$  is the degree of utilisation of capacity [boats per day / boat capacity per day] and  $ot$  is the daily operation time of locks in [hours].

Increases in waiting time are valued using a consumer surplus approach. Consumer preferences for a reduction in waiting time at locks were estimated on the basis of an empirical on site survey of boaters at locks along the Havel waterway ( $n = 420$ ). Details of the survey are given in Meyerhoff & Grossmann (2007). Willingness-to-pay (WTP) for avoiding waiting time at locks was elucidated using a choice experiment format. A mean WTP for reduction of waiting time of 1,2 €/hour and boat was determined. Annual changes of total consumer surplus induced by changes in water availability are then estimated as follows:

$$L_{\_RMüritz_{(t,ds)}} = \sum_m (nT_{(ds)} - T_{(t,m,ds)}) * N_{(t,m,ds)} * WTP$$

where  $nT$  is the nominal average waiting time under current conditions in [hours/boat] and  $T$  is the average waiting time under actual conditions in [hours/boat],  $N$  is the number of boats passing a lock and  $WTP$  is the willingness to pay to avoid waiting time in [€/hour and boat].

### Variables for scenario analysis

Key variables determining demand and loss functions for scenario analysis are changes in utilisation levels. Whereas in the A1 scenario further growth of tourism activity in the region is assumed as a consequence of enhanced economic

growth, no such increases are assumed in the *B2* scenario. Changes in use levels are based on projections developed by PLANCO (2006).

### **Pond fisheries**

The German section of the Elbe River Basin has approximately 62 pond fisheries, which are mainly concentrated in the region of Lusatia in Saxony and Brandenburg, where pond fisheries date back to the 12<sup>th</sup> century. A few pond fisheries can also be found along the Havel River and in Thuringia. The commercially dominant species within the pond fishery sector is the carp, which is raised over a 3 to 4 year long time period. During the past years pond fisheries have increasingly been affected by water scarcity. While trout fisheries are also common in Germany, these are located in the mountainous parts; hence only few commercial trout farms exist in the Elbe region. Trout farms are preferably located in the vicinity of freshwater springs in the mountains and are not included in this study because they are less affected by low flows. All 62 carp pond fisheries are included in the WBALMO Elbe model.

#### *Estimation of water demand and water use*

Fish ponds are filled in spring and drained in autumn. Monthly water demand is estimated based on the amount of water required to compensate evaporation from the pond surface. Water demand of the pond fisheries is estimated as follows:

$$DQ_{(ds,m,t)} = (A_{(ds)} * ETw_{(ds,m,t)}) + V_{(ds)} * rf_{(m)}$$

Where *rf* is the proportion of the total pond volume that is refilled in a specific month, *A* is the total pond area in [ha], *ETw* is the monthly evaporation from water surfaces [m<sup>3</sup>/ha] and *V* is the total volume of the ponds in [m<sup>3</sup>].

The demand estimate corresponds roughly to the effective water use. Return flows occur only in the autumn months when ponds are drained.

#### *Loss function*

Fish production is estimated from the available surface area of standard fish ponds (Messner et al., 2007). Carp pond fisheries typically consist of a number of ponds with a target water depth of 1,1 m. Insufficient water supply causes falling water levels, rise in water temperature, and finally oxygen shortage in the pond waters. As a consequence, there is an increased risk that the fish stock dies. If the water level falls below 0,7 m ponds are therefore usually taken out of production and the water is pumped to stabilise other ponds within the group. For simplification it is assumed that the total water supplied in the production period is proportional to the available pond volume and that the volume is proportional to the water depth of the standard pond. Thus in order to maintain minimum water levels in the range between 1,1 and 0,7 m at least 63,3 % of the demand has to be supplied. If the water deficit is greater, the pond area has to be reduced proportionally to ensure that the remaining pond area can be operated with water levels at the threshold level of 0,7 m. The proportion by which the pond area is reduced in size as a result of a water deficit is therefore calculated as follows:

$$Ared = \text{if} \left( \frac{\sum_{m=3}^{10} SQ}{\sum_{m=3}^{10} DQ} < mcrit, \frac{\sum_{m=3}^{10} SQ}{\sum_{m=3}^{10} DQ} * \frac{1}{mcrit}; 1 \right)$$

and

$$mcrit = \frac{WL \min}{WLn}$$

where mcrit is the threshold defining the proportion of the standard pond volume below which the operational area of the ponds has to be reduced, WLmin and WLn the minimum required and the nominal pond water levels in [m] respectively.

Valuation of losses in the pond fisheries sector is based on a change in net income approach. Changes in fish yield are calculated on the basis of the specific productivity per pond area. Data on yield, revenue, subsidies and costs in the carp fishery sector were taken from SLL (2005). Changes in net income are estimated as follows:

$$L_{-}F_{(ds,t)} = Apond_{ds} * (1 - Ared_{ds,t}) * ((Y * P_t) + ES_t - Cv)$$

Where Apond is the total available pond area in [ha], Ared is the proportion of the pond area actually available, Y is the fish yield in [kg/ha], P is the price in [€/kg], ES is an environmental subsidy related to the external biodiversity benefits of ponds that is granted for operational pond area [€/ha] and Cv are the variable production costs in [€/ha].

#### *Coping and adaptation options*

Coping mechanisms in production are implicitly implemented by assuming that water deficit up to the specified threshold level can be compensated without a reduction in pond area. Beyond this threshold, the remaining water is used to ensure the operation of the remaining pond area.

#### *Variables for scenario analysis*

Key variables that are varied for the scenario analysis are changes in product prices and payments for agri-environmental schemes. It is assumed that in the A1 scenario more fish will be sold at lower wholesale prices and in the B2 scenario that more fish will be sold at higher retail prices. In addition in the A1 scenario subsidies will be fully abolished after a phasing out of ten years, while in the B2 scenario subsidies will be gradually reduced by 50% until 2052.

### **Sprinkler irrigation of agricultural crops**

It is estimated that currently approximately 1,4 - 1,9 % of the agricultural crop is irrigated. In the east German states Thuringia, Saxony, Saxony-Palatinate and Brandenburg, which cover a major share of the Elbe Basin, it is estimated that some 75.000 - 90.000 ha are irrigated (Albrecht 2001). Roughly three quarters of the irrigation water is taken from surface water (reservoirs and rivers) and the remaining quarter from ground water. While irrigation of fodder crops was common during the socialist era, sprinkler irrigation is now applied mainly to high

value crops such as potatoes and field vegetables. In the western German state of Lower Saxony, only parts of which are in the Elbe Basin, some 8 %, regionally up to 80 %, of the crops are irrigated. This corresponds to a total irrigated area of 235.000 ha. Three quarter of the water in this area is taken from groundwater sources. The WBALMO Elbe Model covers 53 000 ha of irrigated crop at 112 demand sites, with an average size of 486 ha per demand site.

### *Estimation of water demand and water use*

The annual irrigation water demand for the irrigated areas is calculated on the basis of the FAO Method (Doorenbos 1975). Crop water requirements are calculated assuming a demand site with simplified evapo-transpiration and crop growth processes. The relationship between evapo-transpiration of a specific crop and the reference condition is integrated into a single coefficient  $k_c$ .

$$ETp_{crop} = ETp_{ref} * Kc_{crop}$$

where  $ETp_{crop}$  is the potential crop evapotranspiration in [mm] for crops,  $ETp_{ref}$  is the reference evapotranspiration in [mm],  $k_c$  is the specific FAO crop evapotranspiration coefficient [-].

Based on this approach, the additional amount of water above the precipitation needed to supply the evapotranspiration demand of the crops at a demand site is calculated as follows:

$$DQ_{ds} = \sum_{crop} \left( \left( \frac{1}{IrrEff} \right) * (Max: (0; (ETp_{ref} * kc_{crop}) - P)) * A_{crop,ds} * 0,1 \right)$$

Where  $A_{ds}$  is irrigated the area per demand site in [ha],  $Fraction_{crop}$  is the fraction of the area covered by a specific crop,  $P$  is precipitation in [mm],  $IrrEff$  is the share of supplied water available for ET (i.e. irrigation efficiency) [-],  $DQ_{ds}$  is the total irrigation water demand at demand site  $ds$  in [m<sup>3</sup>/s].

It is assumed that water demand for irrigation corresponds to effective water use, as all of the modelled water demand is evapo-transpired and there are no return flows.

### *Loss function*

The key effect of reduced water availability for irrigation is a reduction of crop yield. Crop yields are also calculated on the basis of the FAO Method (Doorenbos 1979) in which a linear crop-water production functions is used to predict the reduction of crop yield when crop stress is caused by a shortage of soil water according to the following relationship:

$$1 - \frac{Ya}{Y_{max}} = ky * \left( 1 - \frac{ETa_{crop}}{ETp_{crop}} \right)$$

where  $ky$  is yield response factor (-),  $ETa_{crop}$  is adjusted actual evapotranspiration in [mm],  $ETp_{crop}$  is crop evapotranspiration for standard conditions (no water stress) in [mm],  $Ya$  is actual crop yield in [dt] and  $Y_{max}$  is maximum expected or agronomically attainable crop yield under no stress [dt].

The adjusted actual evapotranspiration is calculated for every month for irrigated (i) and optimally irrigated (io) conditions as follows:

$$ETa_{crop,irr=i} = \min(ETp_{crop}; P + (IrrEff * \frac{SQ_{crop}}{A_{crop}} * 10))$$

$$ETa_{crop,irr=io} = \min(ETp_{crop}; P + (IrrEff * \frac{DQ_{crop}}{A_{crop}} * 10))$$

Where  $SQ_{crop}$  and  $DQ_{crop}$  are the available and demanded irrigation water respectively for a specific crop in [m<sup>3</sup>/s] at a demand site calculated by the WBALMO model.

The actual yield can then be calculated from the annual sum of potential and actual evapotranspiration for each irrigation condition:

$$Ya_{crop,irr} = Y \max_{crop} * \max(0; (1 - ky_{crop} * (1 - (\frac{\sum ETa_{crop,irr}}{\sum ETp_{crop}}))))$$

Loss is calculated using a change in net income approach as follows:

$$L_{IR_{ds,t}} = \sum_{crop} ((Ya_{crop,irr=io,t} - Ya_{crop,irr=i,t}) * A_{crop} * P_{crop,t}) - ((DQ_{ds} - SQ_{ds}) * C_{var})$$

where  $Ya$  is the actual yield in [dt/ha] under optimally irrigated condition (irr=io) and actual conditions (irr=i),  $A$  is the irrigated area in [ha],  $P_{crop}$  is the produce price in [€/dt],  $C_{var}$  are the variable costs for irrigation and water in [€/m<sup>3</sup>] and  $DQ$  and  $SQ$  are the water demand and supply in [m<sup>3</sup>] respectively.

### *Coping and adaptation options*

There are no coping mechanisms implemented, as yield changes in proportion with the water deficit. Irrigation efficiency is assumed to be 100 %.

### *Variables for scenario analysis*

Key variables for scenario analysis are changes in produce prices, changes in crop mix and changes in irrigated crop area. For the current analysis, it is assumed that the area irrigated from surface water sources does not increase and that the sole irrigated crop is potatoes.

## **Sub-irrigated and water table regulated lowland (fen) wetlands**

### *Characterisation*

The lowland region of the Elbe Basin is characterised by large wetland areas, in many sub basins with a share of around 20 % of the total area. Almost all of these wetland areas have been drained in the last centuries and as a result their water table is today regulated by weirs. Because of the negative climatic water balance additional water from the river systems is required to maintain water levels during summer month. The system of regulation and drainage has been

constructed in a manner that allows water transfers and sub-irrigation of the wetlands. Regulated wetlands thus constitute one of the major water users within the lowland river systems. In total 35 wetlands that are larger than 1000 ha were included as water users in the WBALMO Elbe model. They have a total area of 3840 km<sup>2</sup>. Around 50 % of these wetland sites are groundwater influenced sandy soils, while fen soils constitute around 35 % of the area. 54 % of the wetland areas are grassland, 34% are arable and the rest is forest and open water. Irrigation water supplied to maintain water levels delivers multifunctional benefits that are contingent on the ecological functions of the wetland ecosystem, such as agricultural biomass production, greenhouse gas sequestration, habitat function and nutrient retention.

### *Estimation of water demand and water use*

Water demand is estimated with the wetlands water balance sub-model WABI. This model is described in detail by Dietrich et al. (2006) and Dietrich et al. (2008). WABI is a simple water balance model for ground water influenced areas with drainage and sub-irrigation systems. The wetlands areas are divided in sub-areas. A sub-area is the smallest area in which the ground water level can be regulated separately and is a water user in the WBALMO Elbe model. One important assumption is a horizontal ground water level in each sub-area. The model needs target water levels, climatic conditions and inflows for each sub-area as an input and then calculates evapo-transpiration, demand for additional water, actual water levels and return flows.

### *Loss Function*

Water table regulation in wetlands impacts simultaneously on a multitude of ecological functions associated with the wetland, all of which have to be considered in management decisions (Turner et al, 2003). The WBALMO Elbe model takes the agricultural production function, habitat function and greenhouse gas sink / source function into account. Loss is calculated from the difference in benefit accruing from these functions at target water levels and actual water levels.

The loss of agricultural production function is based on the difference in yields. Five agricultural cropping systems are identified on the basis of a combination of land use data and water table levels. Arable land is assumed to be planted with the dominant crop, which is corn. Grassland is classified into four subtypes: intensive grassland (groundwater levels  $\geq 0,45$  m), extensive grassland (groundwater levels  $\geq 0,45$  m), extensive wet grassland (groundwater levels  $< 0,45$  and  $> 0$  m) and reed (groundwater levels  $> 0$  m). Yield is calculated using the FAO method as outlined above, whereby the sum of annual actual evapo-transpiration (ETa) and potential evapo-transpiration (ETp) is provided from the wetlands water balance sub-model. Yields are calculated for three irrigation situations: target water level, actual water level and without groundwater influence. Annual energy yield is calculated using the specific energy density of each crop's biomass and the potential biomass as follows:

$$YE = \sum_{crp} Y_{max_{crp}} * \max(0; (1 - ky_{crp} * (1 - (\frac{\sum ETa_{(crp,m)}}{\sum ETp_{(crp,m)}})))) * ED_{crp} * A_{crp}$$

where YE is the annual energy yield in [MJ], Ymax is maximum expected or agronomically attainable crop biomass yield under no stress in [dt/ha], ky is yield response factor (-),  $ETa_{crp}$  is adjusted actual evapotranspiration for the specific crop in [mm],  $ETp_{crp}$  is crop evapotranspiration for standard conditions (no water stress) in [mm], ED is the specific energy density of the crop in [MJ/dt] and A is the area of crop in [ha].

Total annual energy yield is calculated for target and actual water levels for all crops in the wetland. In addition, the actual annual energy yield per ha for the substitute crop (mais) under conditions without groundwater influence is recorded as a reference. Loss is calculated on the basis of the change in net income approach. Because the energy yield of grass produced for fodder is not directly tradeable in the market, a substitution value is estimated. It is assumed that unexpected deficits in energy yield of the fodder grown in the wetland during dry years are compensated by mais that is grown outside of the wetland for purposes of biogas production. The value of the reduced energy yield in the wetland is thus estimated from the loss of revenue from biogas biomass production. This is estimated from the area required to compensate the reduced energy yield, the specific yield of mais dependant on the climatic conditions of the year and the market price as follows:

$$L\_Wagr_{ds,t} = \frac{(nYE - YE_{t,ds})}{YEcomp_{t,ds}} * (YEcomp_{ds,t} / EDcomp) * convFD * P_t$$

Where nYE and YE are the total annual energy yield at target and actual water levels in [MJ], YEcomp is the specific energy yield of the compensation crop (mais) outside the wetland in [MJ/ha], ED is the specific energy density of the compensations crop's dry matter in [MJ/dt TM], convFD is a factor to convert from dry matter to wet matter (3,03), P is the market price of the compensation crop's (mais) wet biomass for biogas production in [€/ dt FM].

Greenhouse gas emissions from drained fen soils are estimated using the approach of Renger et al. (2002) for CO<sub>2</sub>-C emissions and van den Pol – van Dasselaar et al. (1999) for CH<sub>4</sub>-C emissions. Both estimate regression equations for the relationship between groundwater level and gas release. N<sub>2</sub>O-N Emission are approximated to be 5 kg/ha above and 0 kg/ha below 30 cm water table. The corresponding specific annual emissions of CO<sub>2</sub> equivalents for areas with target water levels lower than the ground level are calculated as follows:

$$CO_{2-C_{wl}} = (113 * WL - 0,5179 * WL^2 - 298)$$

$$CH_{4-C_{wl}} = (EXP(3,57 - 0,08 * WL_{ds,t}) * 10) * 0,75$$

$$N_2O.N_{wl} = if(WL < 30; 0; 5)$$

Where CO<sub>2</sub>-C, CH<sub>4</sub>-C and NO<sub>2</sub>-N are the annual emissions in [kg/ha] and WL is the average annual groundwater level in [cm].

Net emissions are converted into a CO<sub>2</sub>-C equivalent emission by multiplying the emission rate with specific Global Warming Potentials (GWP). Emissions are transformed to CO<sub>2</sub>-C equivalents using element based GWP for a 100 year time horizon of 1 for CO<sub>2</sub>-C, 4 for CH<sub>4</sub>-C and 172 for N<sub>2</sub>O-N (Renger et al. 2002) and finally the total annual CO<sub>2</sub>-C equivalent emission is then calculated as follows:

$$CO_2.Ceq_{ds,t} = \sum_{wl} A_{wl,ds,t} * (CO_2.C_{wl} * GWP_{CO_2} + CH_4.C_{wl} * GWP_{CH_4} + N_2O.N_{wl} * GWP_{N_2O})$$

where A is the fen area in [ha] with an average annual groundwater water level wl in year t and GWP is the specific greenhouse warming potential.

The change in greenhouse gas emissions resulting from a change in average annual water level is valued using a replacement cost approach. The replacement cost method is based on the assumption, that changes in additional greenhouse gas emissions from wetlands must at least hypothetically be offset by an equivalent reduction in another place. It can be valued with the marginal abatement costs within the economy to offset this emission. The marginal abatement costs in the economy describe the least cost alternative to meet the overall greenhouse gas reduction policy targets. We apply the recommendations of the German Environmental Agency (UBA, 2007) and use a value of 70 €/t CO<sub>2</sub>. The loss incurred from increased greenhouse gas emissions are then calculated as follows:

$$L\_Wgg_{ds,t} = (nCO_2.Ceq - CO_2.Ceq_{t,ds}) * 3,7 * RC_t$$

where nCO<sub>2</sub>eq are the nominal total greenhouse gas emissions at target water levels and CO<sub>2</sub>eq are greenhouse gas emissions under actual conditions in [kg CO<sub>2</sub> equivalents] and RC are the replacement costs in [€/kg CO<sub>2</sub>].

Changes in habitat or biodiversity quality are estimated using as an indicator the area of peat wetland soils with an average annual water level less than 40 cm below surface. This water level corresponds to the target water levels for wetland conservation as set out in the regional wetland management strategy (LUA, 1997). For the assessment, environmental compensation payments granted to farmers for high water levels on their land are used as a lower bound proxy for willingness to pay. In the particular case of environmental enhancements obtained for grassland from water level management it has been proposed that the enhanced rate for water level management payable under some agri-environmental schemes can be used as a surrogate annual value for the environmental benefit of such management in cost-benefit analysis (cf. MAFF 1999). In the reverse situation, where payments have been made to enable high water levels but these water levels are not achieved due to a lack of sufficient water supplies, these payments may then have to be considered as losses because the expected benefit is not being realised. Brandenburg holds the majority of the wetland area included in the model. The payments granted in Brandenburg for the maintenance of high groundwater levels on grasslands ranges from 10 – 60 €/ha plus an additional compensation for the necessary shift from extensive to very extensive grassland use ranging from 35 -110 €/ha (MLUV, 2005). For this analysis we use a value of 170 €/ha. Total annual loss is then assessed on the basis of the difference of area with high water table levels under target and actual conditions as follows:

$$L\_Whab_{ds,t} = (nAwet - Awet_{t,ds}) * WTP_t$$

Where L\_Whab is the loss from wetland habitat degradation (€), nAwet and Awet are the area of peat wetland with groundwater level below surface < 40 cm in [ha] for nominal water levels and actual conditions respectively, WTP is the annual compensation granted to farmers for wetland habitat protection in [€/ha].

The total loss for wetlands is the sum of losses from changes in agricultural production, greenhouse gas emissions and habitat functions.

### *Coping and adaptation options*

The main adaptation options are to be found in changes of water level regulation and the associated changes in land use. Additional options include alternative water allocation rules within each of the wetland sites, for example to give preference to certain areas.

### *Variables for scenario analysis*

Potential variables for scenario analysis are changes in replacement costs for reduction of CO<sub>2</sub> equivalents, changes in price for biogas biomass and changes in the willingness-to-pay for habitat conservation in wetlands. Changes in land use are contingent on changes in water level regulation and constitute a further option for analysis of management options. For the present analysis, all parameters were assumed to be constant. Water level management options are explored in Dietrich et al. (2008) and Lienhoop et al. (2008).

## **Selected results**

### **Water use in the Czech and German Elbe Basin**

In order to understand the risks associated with low flows for different sectors, we at first present the relative dimensions of water use and possible changes in time for important water users in the basin. A summary of the main off-stream water uses included in the model is given in and Figure 1 for the Czech and German parts of the basin. Figure 2 compares average annual demand, average annual actual supply and consumptive use (supply net of return flows) for the base period (2003 – 2007) for the German part of the basin. In addition the expected changes under scenario A1° STAR T2 and B2+ START T2 as they are included in the WBALMO model runs are reported in Figure 3, also for the German basin.

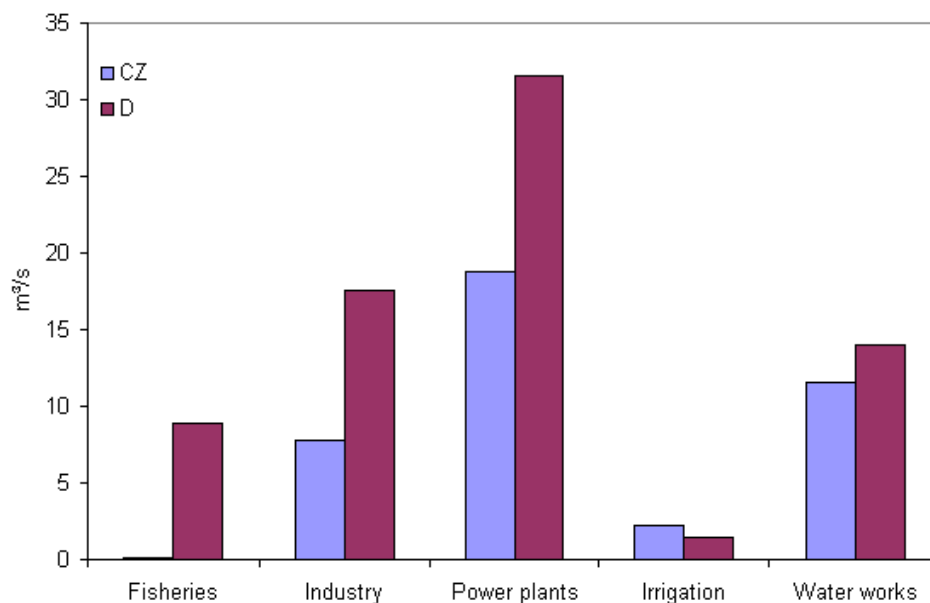


Figure 1: Estimate of the total average annual demand for water withdrawal or through flow for the main water uses for the German (D) and Czech (CZ) basin for the Period 2003-2007.

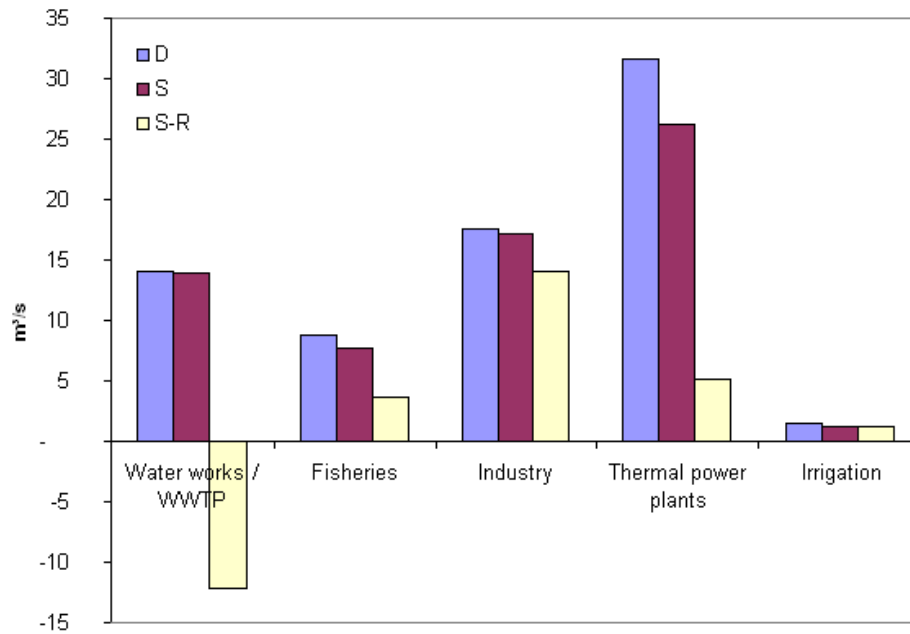


Figure 2: Estimate of the total average annual demand for water withdrawal (D), water supply (S) and consumptive use (S-R) for the main water uses for the German basin for the period 2003-2007.

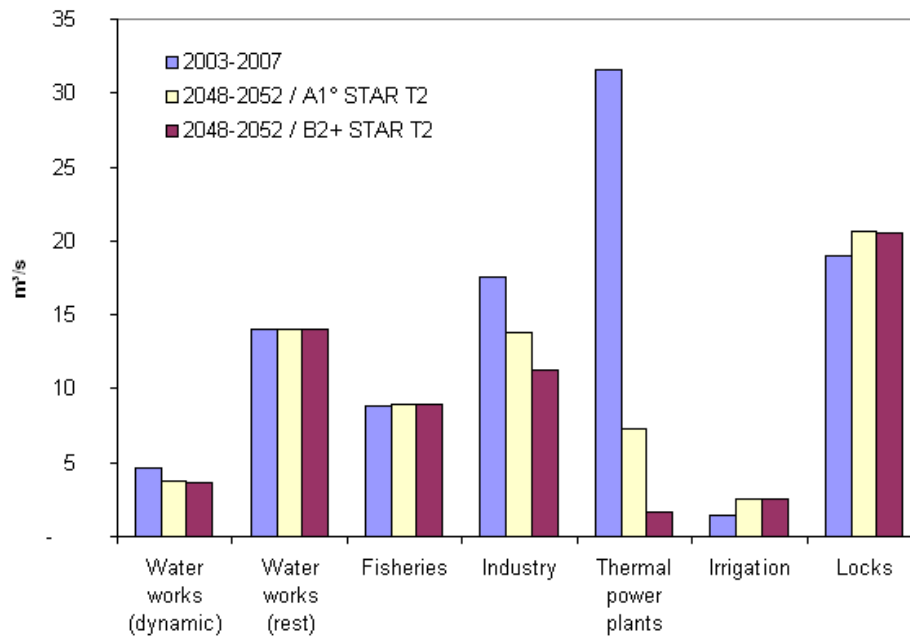


Figure 3: Estimate of total average annual demand for water withdrawal for the main water uses for the German basin for the period 2003-2007 and for two baseline scenarios for the period 2048-2052.

The largest demand for water is by thermal power plants that have an annual demand of ca. 35 m<sup>3</sup>/s. The consumptive use is on average only ca. 20 % of the actual withdrawal. The total surface water demand decreases significantly, depending on scenario, by 30 -80 % from the period 2003-2007 to 2048-2052. The water deficit of the sector improves over this period from on average ca. 20 % to 0 %. This is a result of the change in power plant stock and associated changes in cooling technology (cf. Vögele 2008). Industrial water demand is ca. 20 m<sup>3</sup>/s of which ca. 70 % is consumptive use. Total industrial surface water demand decreases by 20-40 % over the period of analysis. The average water deficit of the sector increases very little over this period from on average ca. 5 % to 6 %. Public water supply utilities in total abstract ca. 14 m<sup>3</sup>/s. Approximately 4 m<sup>3</sup>/s are abstracted from the drinking water reservoirs, the remaining water is abstracted mainly by the way of bank filtration. Return flows occur via the waste water treatment plants. While water supply utilities in the German part of the sub-basin abstract ca. 14 m<sup>3</sup>/s, waste water treatment plants return ca. 26 m<sup>3</sup>/s that the public water supply and sewerage infrastructure is a net inflow to the surface water system. This is of course the result of the additional transfer of groundwater and storm water via the sewerage system into the surface water system. The total water demand for water abstraction from the reservoirs (with a dynamic water demand function) decreases by ca. 0 - 15 %. The water demand for the other abstraction was held constant. The water deficit of the sector increases over this period from on average ca. 1 % to 5 %. The water demand of pond fisheries is roughly 9 m<sup>3</sup>/s. Approximately 45 % of the withdrawal is consumptive water use. Total surface water demand increases only very slightly by ca. 1 % over the period of analysis, but the water deficit of the sector increases from on average ca. 13 % to 25 %. Agricultural sprinkler irrigation has water demands of ca. 3,4 m<sup>3</sup>/s of which there are no return flows. Total surface water demand increases to 234 %. This is a direct effect of the increased water demand for evapo-transpiration of the crops, as the irrigated area is assumed to be constant. The average water deficit of the sector increases from ca. 20 % to 45 %. Demand for additional water for sub-irrigation of wetlands also rises with increased evapo-transpiration. The average annual demand for additional irrigation water to compensate for negative climatic balance in the summer for the period 1962-90 of the 32 wetland sites is estimated to be ca. 36 m<sup>3</sup>/s. Wetlands thus constitute the second largest off-stream demand for water in the Elbe basin following the thermal power plants. In-stream water users have high nominal demands for flows, but the water is returned to the river immediately. The hydropower stations of the German part of the Elbe Basin and included in the model alone have a demand of ca. 1277 m<sup>3</sup>/s. Demand of hydropower stations remains constant because no major extensions or closures were assumed. The average water deficit of the sector increases over the period of analysis from ca. 27 % to 39 %. Total demand for minimum water flows required for the operation of locks on the waterways is almost constant too and is roughly 19 m<sup>3</sup>/s on the waterways of the German part of the Elbe basin. The average water deficit of the locks on the waterways of the Havel sub-basin, that is of interest for recreational boating, increases from ca. 2 % to 8 %.

### **Economic assessment of risk associated with low flows in the German Elbe Basin.**

Two highly aggregated indicators to describe the risk associated with low flows are presented. The first describes the equivalent annual average annual loss by sector and river basin. It represents the discounted net present value of the

average annual losses from 2003 – 2052. This is transformed into an equivalent annual value to facilitate comparability<sup>1</sup>. This highly integrated indicator enables a comparison of the distribution of risk amongst sectors and basins. The second indicator describes the change of average annual losses from the period 2003-2007 to 2048 – 2052. This indicator gives a rough estimate of the expected effects (or “costs”) of climate change, again differentiated by sectors and river basins. Both indicators are presented for the two baseline scenarios (A1° STAR T2 and B2+ STAR T2) to reflect effects of divergent pathways of socio-economic development. In addition, the range of the losses is given if one takes the dryer and wetter climate scenarios (STAR T2 f and STAR T2 t) into account.

The equivalent annual average loss (Figure 4) show that the total sectoral risk associated with low flows is highest for hydropower, agricultural sprinkler irrigation and water uses for sub-irrigation of wetlands. It is followed in decreasing order, by water uses for industry, recreational boating on inland waterways, pond fisheries, power plants, recultivation of mining pits and public water supply. The change in annual average loss from the period 2003-2007 to 2048 – 2052 in absolute values gives a similar ranking (Figure 5): water uses for agricultural sprinkler irrigation, sub-irrigation of wetlands, hydropower and recreational boating are the uses associated with the largest absolute increase in losses. Pond fisheries and industry have lower total changes in losses. A comparison based on the relative change from the period 2003-2007 to 2048 – 2052 gives a slightly different picture: losses from water uses for agricultural sprinkler irrigation increase by ca. 70 %, for sub-irrigation of wetlands increase by ca. 90 %, for hydropower by ca. 80 %, for industry by 20 %. Larger relative changes are experienced by fish ponds, whose losses increases by 260 % and recreational boating, where losses begin to appear for the first time within the period from 2007 – 2052.

The difference both in equivalent annual average loss and change in annual average loss between the two baseline scenarios (A1° STAR T2 and B2+ STAR T2) is generally lower than the range given between the wet and dry variations of the climate scenario, indicating that the assumed range of possible changes in regional climate have a more profound impact on expected losses than the assumption with regard to the range of socio-economic drivers that have been included in the model. A notable exception is the losses of the hydropower sector, where the differing assumptions about the development of electricity prices result in marked differences between the baseline scenarios. Marked differences between the baseline scenarios can also be observed for recreation use of inland waterways, which is a result of differing assumptions about the intensity of recreational use. Differences in the production volume between the two scenarios are the cause of variation in the industrial sector. Differences in the pond fisheries can be traced back to assumptions about differences in produce prices. Similar differences are to be expected for the irrigation and wetlands water use, if variable assumptions regarding prices of agricultural produce were to be made, but these prices were held constant for this analysis.

---

<sup>1</sup> A discount rate of 3% is used throughout.

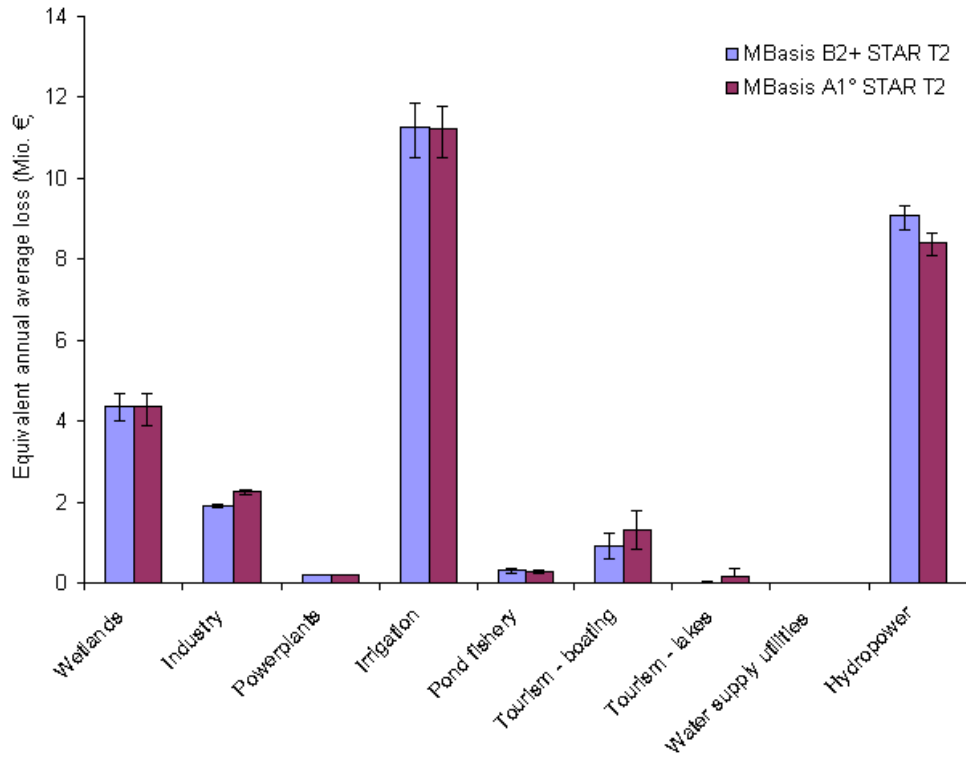


Figure 4: Equivalent annual average loss by water uses for the analysis period 2003-2052 for two baseline scenarios. The range denotes the wet and dry climate projection variants.

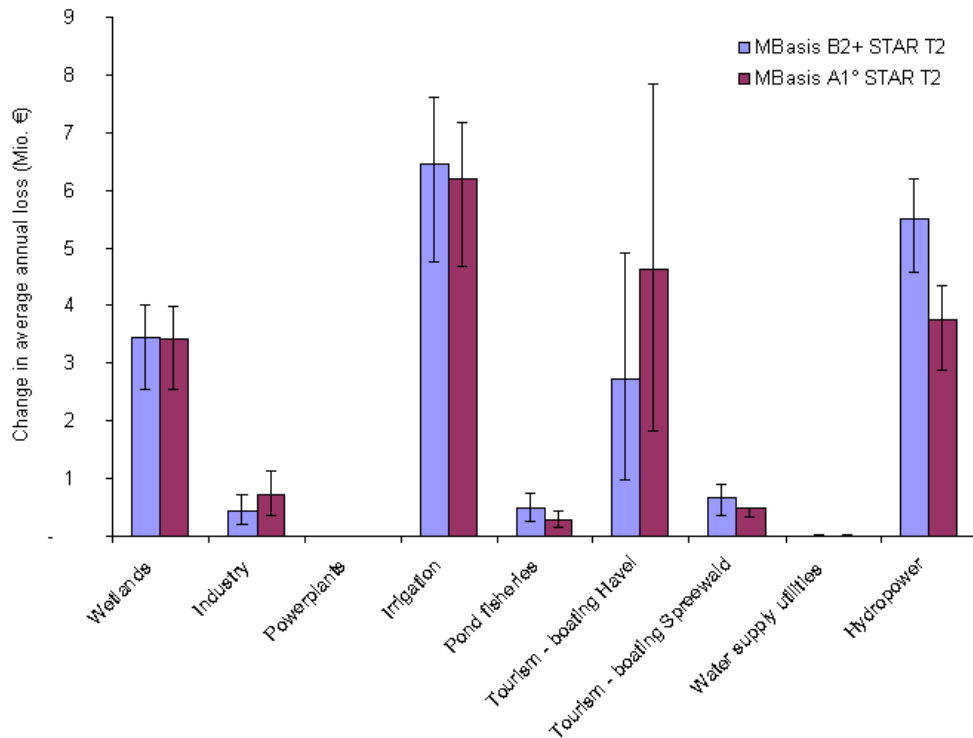
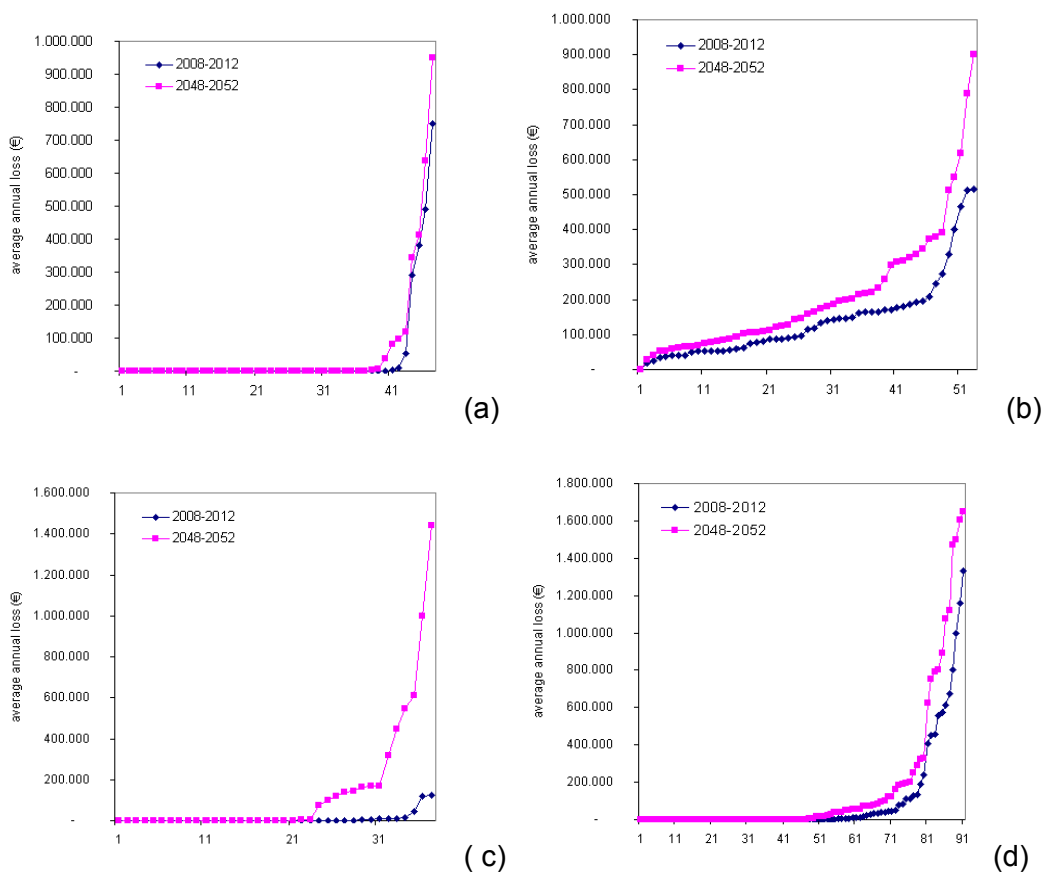


Figure 5: Change in total average annual loss by water uses from the period 2003-2007 to the period 2048-2052 for two baseline scenarios. The range denotes the wet and dry climate projection variants.

Figure 6 shows the distribution of average annual losses amongst all demand sites for the major water uses. It is presented as a comparison for the period 2008-2012 and 2048-2052. Because the public water supply sector and the thermal power plants basically experience only very small losses they are not discussed in more detail here. Of special interest is the share of total demand sites that experience any losses at all. This share is larger than 50 % of the demand sites for hydropower and wetlands and larger than 25 % of demand sites for sprinkler irrigation and pond fisheries for both comparison periods. Only recreational boating experiences a marked change in share from less than 25 % to more than 25 % as time progresses. Ca. 40 % of the hydropower demand sites have average annual losses larger then the average of the sector, ca. 20 % of the wetland, pond and irrigation demand sites have average annual losses larger than the average of the demand sites and ca. 10 % of the locks and industrial demand sites are responsible for losses larger than the average. The implication of this result is that losses in general occur only at less than 50 % of the demand sites and less than 20 % of the considered demand sites are responsible for the largest share of total losses. Exceptions are hydropower plants and wetlands, of which nearly all site are affected. A second implication of this result is that the effects of reduced water availability over the period of analysis will exacerbate existing shortages rather than inducing losses at hitherto unaffected sites.



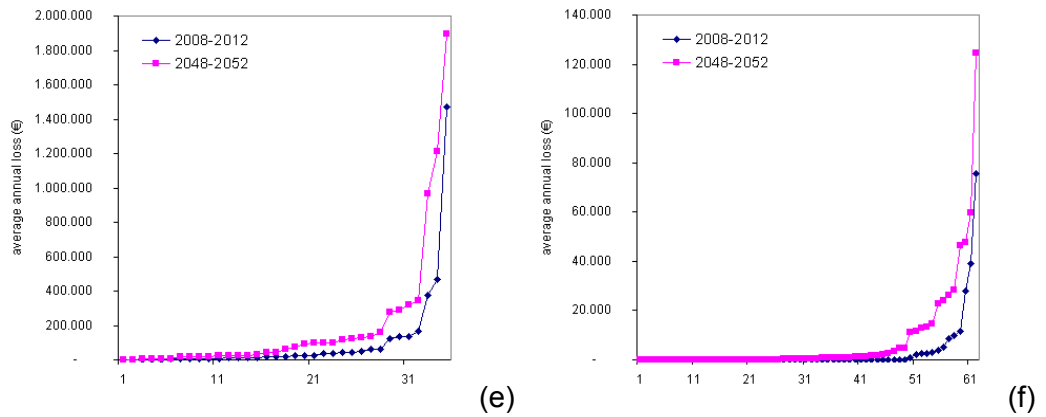


Figure 6: Average annual loss for every demand site arranged in rising order for the period 2003-2007 and the period 2048-2052 for the *MBasis A1° STAR T2* baseline scenario. (a) industry (b) hydropower (c) recreational boating (d) irrigation (e) wetlands (f) pond fisheries.

The spatial distribution of losses by sub-basin is presented again using the indicators equivalent annual average loss (Figure 7) and change in average annual loss (Figure 8). Sub basins were aggregated so as to be of roughly equal sizes and to correspond roughly to major management units. Maps of the German section of the Elbe Basin showing the distribution of average annual loss by demand site and sector for the period 20048-2052 are presented in Figure 9. It is apparent that the absolute largest losses and changes in loss are to be found in the lowland river basin of the Havel. The relative changes are highest in the Saale, where losses increase by 130 - 170 %, followed by the Havel with increases of ca. 90 – 110 %. The remaining basins have increases ranging from 20 – 70 %. The regional pattern reflects both the differences in water supply and the distribution of the particularly vulnerable water users within the basin. The river Havel River Basin contains a large share of the sub-irrigated wetlands and agricultural sprinkler irrigation sites. Its main rivers are part of the waterway system that is used for recreational purposes. The rivers Mulde and Saale hold a major share of the hydropower capacity. A more detailed analysis of the factors determining water availability in these basins is provided by Kaltofen et al. (2008) and Dietrich et al. (2008).

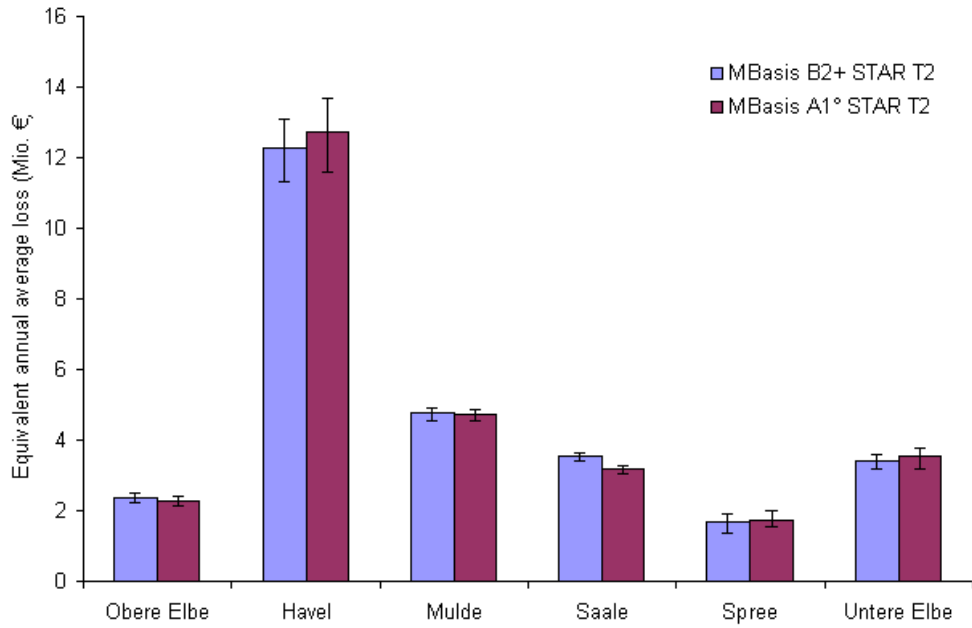


Figure 7: Equivalent annual average loss by sub-basins for the analysis period 2003-2052 for two baseline scenarios. The range denotes the wet and dry climate projection variants.

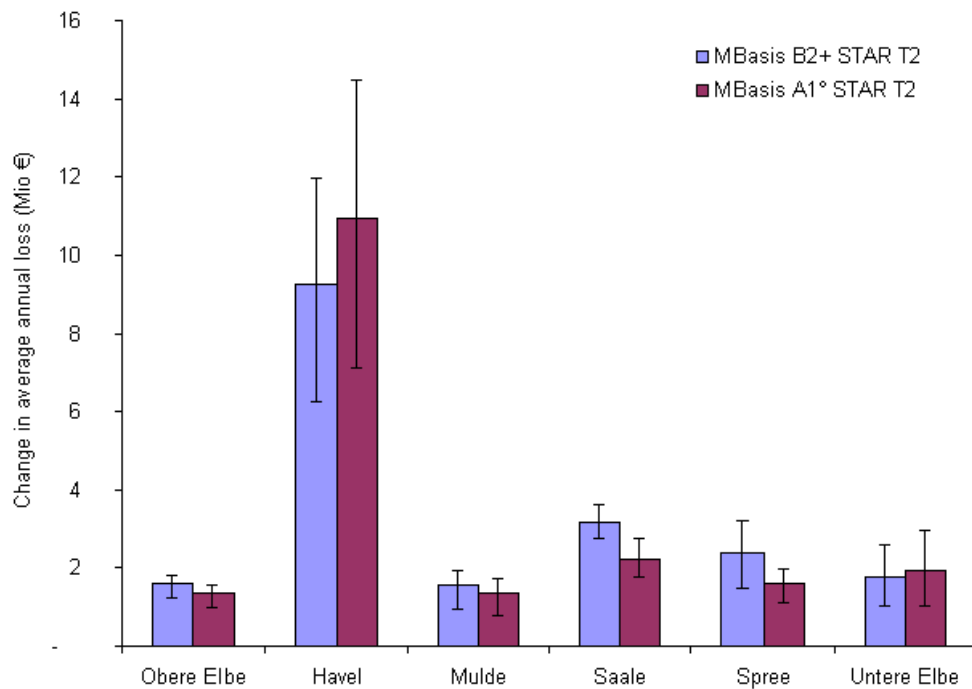


Figure 8: Change in total average annual loss by sub-basin from the period 2003-2007 to the period 2048-2052 for two baseline scenarios. The range denotes the wet and dry climate projection variants.

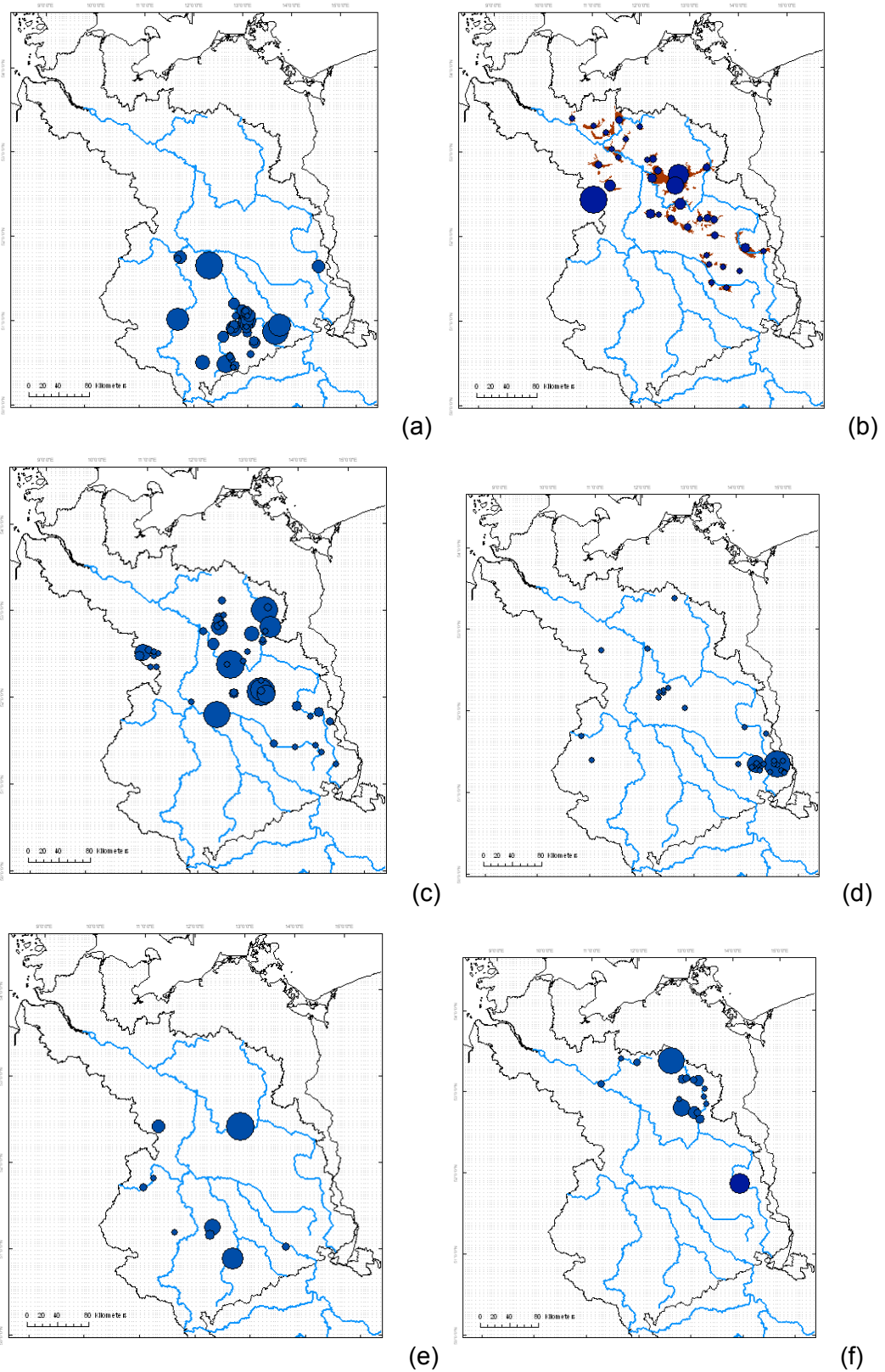


Figure 9: Maps of the German section of the Elbe Basin showing the distribution of average annual loss by demand site and sector for the period 20048-2052 for the baseline scenario *MBasis A1° STAR T2*. (a) hydropower (b) wetlands (c) irrigation boating (d) pond fisheries (e) industry (f) recreational boating.

## Discussion

This paper presents a method to incorporate an economic valuation approach into a river basin model to analyse water scarcity. A key methodological innovation is the development of demand and economic valuation functions for water uses in the Elbe Basin and their integration into an existing water resource modelling framework, WBalMo. The resulting improved model is intended to provide planning information that is currently unavailable. Previously this kind of economic assessment was conducted using a loose mix of separate approaches or was considered infeasible. The developed method of studying the impact and adaptation to climate change incorporates a wider range of factors, such as changes in the projected demand and water uses, such as recreational and wetland water uses, than has been customary in water resource planning to date. The data covering the complete basin is an assemblage from various sources that are not easily available in a transboundary and federally organised water management setting. While attempts have been made to secure data quality, gaps and disagreements between sources do exist. The systematic assembly and reconciliation of data for such a large system is a major product of a model development process, unglamorous though it is. The major conclusion of this work is that it is possible to conduct an integrated analysis for systems as large and complex as the Elbe Basin. In principle the development of economic valuation functions for most productive water uses is not very difficult, it is the availability of data describing users is the main challenges of large scale modelling. This is not so much true for the inclusion of recreational and environmental water uses that have proven to be of major importance within this study. The difficulty arises in developing the correct methodological approach for the valuation of the non-market benefits. Because virtually no secondary data for these types of uses exists, the parameters of the valuation functions have to be determined by conducting empirical studies.

The results of this model, despite their practical and theoretical limitations point to interesting and practical conclusions for water planning over the long term. The results enable a concise picture of the current water scarcity in the basin and potential focal sectors and basins to be developed. Hydropower plants, sub-irrigated wetlands, sprinkler irrigation and instream flow demand for recreation use of waterways, pond fisheries and to some further extent industrial water uses are the major affected water uses both under current and future conditions in the German part of the basin. The increased water demand resulting from increased evapo-transpiration demands of agricultural crops and wetlands on the one side and the instream water uses that are sensitive to variation in flows on the other side, are to be expected to be most at risk from climate change in the basin. Industrial, thermal power generation and municipal uses are affected to a lesser extent and in addition benefit from reduction in demand associated with the projected population economic and technological development in the basin. The results show that in general losses are only observed at less than 50 % of the demand sites and less than 20 % of the considered demand sites are responsible for the largest share of total losses. Exceptions are hydropower plants and wetlands, of which nearly all site are affected by changes in water availability. A further implication of the results is that the effects of reduced water availability will tend to exacerbate existing shortages rather than induce losses at hitherto unaffected demand sites. This is an interesting result, as it implies that management attention may be focused on already observable water management problems and that is not to be expected that major new hotspots will develop. On the other side this implies that the economic implications of current water management controversies will increase, potentially raising the intensity of existing water management conflicts.

Whilst an effort has been made to consider coping mechanisms, complex models like the the WBalMo Elbe are unlikely to be able to represent the full range of coping options and so might be pessimistic in many regards. Whilst adaptation options, that remain to be addressed in detail, may reduce the impact, it is to be expected that there will be much less leeway in the system compared to current operations. The challenge to adequately capture the whole range of possible adaptation options such as improvements in infrastructure operation, demand management or changes in water allocation mechanisms remains for the further development of this modelling approach. Other aspects for improvement include a more detailed consideration of substitution mechanisms with groundwater and possibilities for conjunctive management. In this context also the consideration of changes in demand for additional irrigation area might be of interest. As the database of the model is extended, a more homogeneous coverage of the German and Czech Elbe Basin for all users is intended. Major uses that still have to be considered in more detail include transport shipping, environmental flows related to water quality and the multifunctional use of reservoirs for purposes of flood protection and recreation.

## Acknowledgements

This work was funded by the BMBF GLOWA Elbe Program under FKZ: 01 LW 0307.

## References

- Aerts, J.; Droogers, P. (2004). Adaptation for regional water management. In Aerts, J. C. J. H.; Droogers, P. (Eds.), *Climate change in contrasting river basins: Adaptation strategies for water, food and environment*. Cambridge, MA, USA: CABI. pp.1-24.
- Ahmad, M., Kutcher, G P (1992): *Irrigation Planning with Environmental Considerations - A Case Study of Pakistans's Indus Basin*. Tech. Report., The World Bank.
- Albrecht, M. (2001) Informationen zur Bewässerung im Freiland. Berechnungsring Thüringen und Fachverband für Feldberechnung.
- Ansmann, T. (2008) Wasserbedarf aus Industrie und Kommunen – Öffentliche Wasserversorgung. In: *Wirkungen des globalen Wandels auf den Wasserkreislauf im Elbegebiet – Risiken und Optionen*. Schlussbericht zum BMBF Vorhaben GLOWA Elbe II, Kapitel 2.8
- Booker, J.F. (1995): Hydrologic and Economic Impacts of Drought under Alternative Policy Responses. *Water Resources Bulletin*, 31(5): 889-906
- Booker, J., B. Colby. (1995): Competing Water Uses in the Southwestern United States: Valuing Drought Damages. *Water Resources Bulletin*, 31(5): 877-88.
- Booker, J.F., R.A. Young. (1994): Modelling Intrastate and Interstate Markets for Colorado River Water Resources. *Journal of Environmental Economics and Management* 26(1): 66-87.
- Cai, C., McKinney D., Lasdon, L. (2003) Integrated Hydrologic-Agronomic-Economic Model for River Basin Management *J. Water Resour. Planning and Management*, 129(1):4-17
- Conradt, T.; Hattermann, F.F.; Wechsung, F. (2008) Simulation von räumlich differenzierten Abflussdargebotsszenarien für das Elbegebiet mit dem ökohydrologischen

Modell SWIM. In: Wirkungen des globalen Wandels auf den Wasserkreislauf im Elbegebiet – Risiken und Optionen. Schlussbericht zum BMBF Vorhaben GLOWA Elbe II, Kapitel 2.2

Dietrich, O. Pavlik, D. Schweigert, S. Steidl, J. (2008) Der Wasserhasuhalt großer Feuchtgebiet im Elbe-Tiefland unter den Bedingungen des globalen Wandels – Auswirkungen und wasserwirtschaftliche Optionen. In: Wirkungen des globalen Wandels auf den Wasserkreislauf im Elbegebiet – Risiken und Optionen. Schlussbericht zum BMBF Vorhaben GLOWA Elbe II.

Dietrich, O., M. Redetzky & K. Schwärzel (2007): Wetlands with Controlled Drainage and Subirrigation Systems - Modelling of the Water Balance. *Hydrological Processes* 21(14): 1814-1828, DOI: 10.1002/hyp.6317.

Doorenboos, J., Kassam, A. (1979) Yield response to water. FAO Irrigation and Drainage Paper 33, Rome

Doorenboos, J., Pruitt, W. (1975) Guidelines for predicting crop water requirements. FAO Irrigation and Drainage Paper 24 Rome.

Draper, A. J., Jenkins, M. W., Kirby, K. W., Lund, J. R., and Howitt, R. E. (2003). Economic-engineering optimization for California water management. *J. Water Resour. Plan. Manage.*, 129(3), 155–164

Eiswerth, M. Englin, J. Fadali, E., & Shaw, D. (2000): The value of water in water-based recreation: A pooled revealed preference/contingent behavior model, in: *Water Resources Research*, Vol. 36, No.4, pp. 1079-1086

Füssel, H.-M. (2007): Vulnerability: A Generally Applicable Conceptual Framework for Climate Change Research. *Global Environmental Change* 17(2):155-167.

Gerstengarbe, F-W., Werner, P., Orlowsky, B. Wodinsik, M (2008) Modellierung der regionalen Klimaentwicklung. In: Wirkungen des globalen Wandels auf den Wasserkreislauf im Elbegebiet – Risiken und Optionen. Schlussbericht zum BMBF Vorhaben GLOWA Elbe II.

Gross, D. & Harris, C.M. (1998): *Fundamentals of Queueing Theory*. Wiley.

Grossmann, M. (2005): Berücksichtigung des Wertes von Feuchtgebieten bei der ökonomischen Analyse von Bewirtschaftungsstrategien für Flussgebiete: Beispiel Spreewaldniederung. In Wechsung, F., Becker, A. & Graefe, P. (Hrsg.): *Integrierte Analyse der Auswirkungen des globalen Wandels auf Wasser, Umwelt und Gesellschaft im Elbegebiet. Auswirkungen des globalen Wandels auf Wasser, Umwelt und Gesellschaft im Elbegebiet*. Weißensee Verlag: Berlin, s 304-325.

Haab, T. & McConnell, K. (2002): *Valuing Environmental and Natural Resources*. Cheltenham

Hoymann, J.; Dekkers, J.; Koomen, E.; Scholten, H. (2008) Szenarien der Landnutzung und Landbedeckung im Elbeinzugsgebiet. In: Wirkungen des globalen Wandels auf den Wasserkreislauf im Elbegebiet – Risiken und Optionen. Schlussbericht zum BMBF Vorhaben GLOWA Elbe II, Kapitel 2.4

Jenkins, M. W., Lund, J. R., and Howitt, R. E. (2003). Using economic loss functions to value urban water scarcity in California. *J. Am. Water Works Assoc.*, 95(2).

Kaden S., Schramm M., Redetzky M. (2005): Großräumige Wasserbewirtschaftungsmodelle als Instrumentarium für das Flussgebietsmanagement. - In: *Konzepte für die nachhaltige Entwicklung einer Flusslandschaft*. Bd. 6: Auswirkungen des globalen Wandels auf Wasser, Umwelt und Gesellschaft im Elbegebiet (GLOWA Elbe). Hrsg. Wechsung, F., Becker, A. & Gräfe, P. Weißensee Verlag, Berlin, S. 223 - 233.

Koch, H., Kaltofen, M., Grünewald, U., Messner, F., Karkuschke, M., Zwirner, O., and Schramm, M., 2005, Scenarios of water resources management in the Lower Lusatian mining district, Germany: Ecological Engineering. The Journal of Ecotechnology, v. 24, p. 49-57.

Koch, H., Kaltofen, M., Schramm, M., Grünewald, U. (2006). Adaptation strategies to global change for water resources management in the Spree river Catchment, Germany. Intl. J. River Basin Management, 4 (4), 273-281.

Landesanstalt für Landwirtschaft Brandenburg (LLB)(2001): Datensammlung für die Betriebsplanung und die betriebswirtschaftliche Bewertung landwirtschaftlicher Produktionsverfahren im Land Brandenburg

Landesumweltamt Brandenburg (LUA)(1997): Entscheidungsmatrix als Handlungshilfe für die Erhaltung und Wiederherstellung von Bodenfunktionen in Niedermooren, Fachbeiträge des LUA 27: Postdam

Lienhoop, N. and Messner, F., (in prep): The economic value of allocating water to post-mining lakes in East Germany (submitted to International Journal of Water Resource Development).

Lienhoop, N., Grossmann, M. Koch, H. (2008): Vulnerabilität durch Wasserknappheit im Kontext des globalen Wandels: Eine ökonomische Analyse von Szenarioeffekten und Wassermanagementstrategien. In: Wirkungen des globalen Wandels auf den Wasserkreislauf im Elbegebiet – Risiken und Optionen. Schlussbericht zum BMBF Vorhaben GLOWA Elbe II.

MAFF (1999): Flood and coastal defence project appraisal guidance. Ministry of Agriculture, Fisheries and Food, United Kingdom.

McKinney, D. Cai, C., Rosegrant, M. Ringler, C. Scott, C. (1999) Modeling water resources management at the basin level: review and future directions. SWIM Paper 6, International Water Management Institute.

Messner, F., Koch, H., Kaltofen, M. (2007). Integration Of Economic Evaluation Into Water Management Simulation. In: Erickson, J., Messner, F., Ring, I. (Hg.), Ecological Economics of Sustainable Watershed Management, Advances in the Economics of Environmental Resources, Vol.7, 229-263. Amsterdam: Elsevier Science.

Messner, F., Zwirner, O., Karkuschke, M., (2006): Participation in Multicriteria Decision Support for the Resolution of a Water Allocation Problem in the Spree River Basin: Land Use Policy, v. 23, p. 63-75.

Meyerhoff, J., Grossmann, M. (2007): Queuing in Front of Locks: Recreational Skippers' Willingness to Pay for Passing Through Faster. Working Papers on Management in Environmental Planning 018/2007, TU Berlin.

Ministerium für Ländliche Entwicklung, Umwelt und Verbraucherschutz (MLUV) (2005): Grundsätze und Programme des Vertragsnaturschutzes 2005/2006 in Brandenburg. Brandenburg.

Ministry of Agriculture, Fisheries and Food (MAFF) (1999): Flood and Coastal Defence Project Appraisal Guidance – Economic Appraisal. United Kingdom.

Mutafoglu, K. (2008) Wassernutzung und Wassernachfrage der Industrie im Elbeeinzugsgebiet. In: Wirkungen des globalen Wandels auf den Wasserkreislauf im Elbegebiet – Risiken und Optionen. Schlussbericht zum BMBF Vorhaben GLOWA Elbe II, Kapitel 2.6

Mutafoglu, K. (2008) Wassernutzung und Wassernachfrage der Industrie im Elbeeinzugsgebiet. In: Wirkungen des globalen Wandels auf den Wasserkreislauf im

Elbegebiet – Risiken und Optionen. Schlussbericht zum BMBF Vorhaben GLOWA Elbe II, Kapitel 2.7

Obeng-Asiedu, P. (2004): Allocation Water Resources for Agricultural and Economic Development in the Volta River Basin. Doctoral thesis, University of Bonn, Germany

PLANCO (2006): Beschäftigungspotenziale des Tourismus in den ländlichen Regionen der neuen Bundesländer. BBR-Online Publikationen 1/2006. Bundesamt für Bauwesen und Raumordnung.

Renger, M., Wessolek, G., Schwärzel, K., Sauerbrey, R., Siewert, C. (2002) Aspects of peat conservation and water management. *J. Plant. Nutr. Soil Sci.* 165: 487-493.

Ringler, C. (2001) Optimal Allocation and use of water resources in the Mekong river Basin: multi country and intersectoral analyses. *Development Economics and Policy* 20, Peter Lang Verlag

Ringler, C., Cai, C. (2006): Valuing fisheries and wetlands using integrated economic-hydrological modelling – Mekong River Basin. *Journal of Water Resources Planning and Management* 132 (6): 480-487

Rosegrant, M., Ringler, C., McKinney, D., Cai, C, Keller, A. Donoso, G. (2000) Integrated economic-hydrologic water modeling at the basin scale: the Maipo river basin. *Agricultural Economics* 24 (1) 33-46.

Sächsische Landesanstalt für Landwirtschaft (SLL), (2005): Ökonomie der Karpfenteichwirtschaft. Schriftenreihe der Sächsischen Landesanstalt für Landwirtschaft, Heft 1.

Smit, B., Wandel, J. (2006): Adaptation, Adaptive Capacity and Vulnerability. *Global Environmental Change*, 16(3): 282-292.

Smit, B., Pilifosova, O. (2003): From adaptation to adaptive capacity and vulnerability reduction. In J. Smith, R. T. J. Klein and S. Huq (eds.), *Climate Change, Adaptive Capacity and Development*. London: Imperial College Press, pp. 9-28.

Statistisches Bundesamt (STABU) (2007). Kostenstruktur der Unternehmen des Verarbeitenden Gewerbes sowie des Bergbaus und der Gewinnung von Steinen und Erden 2005, Statistisches Bundesamt Fachserie 4.

Tanaka, S. K.; Zhu, T.; Lund, J.R.; Howitt, R.E.; Jenkins, M.W.; Pulido, M.A.; Tauber, M.; Ritzema, R.S.; Ferreira, I.C. (2006) Climate Warming and Water Management Adaptation for California, *Climatic Change*, 76, 3-4, 361-387

Turner, R. K., van den Bergh, J. C. J. M., Soderqvist, T., Barendregt, A., van der Straaten, J., Maltby, E. and van Ierland, E. C. (2000): Ecological-economic analysis of wetlands: scientific integration for management and policy, *Ecological Economics* 35(1): 7-23

Turner, R.K., van den Bergh, J.C.J.M. and Brouwer, R. (eds.)(2003): *Managing Wetlands: An Ecological Economics Approach*, Edward Elgar, Cheltenham,

Umweltbundesamt (UBA) (2007): Ökonomische Bewertung von Umweltschäden. Methodenkonvention zur Schätzung externer Umweltkosten. Umweltbundesamt, Dessau.

UN/ISDR (2004): *Living with Risk. A global review of disaster reduction initiatives*. Inter-Agency Secretariat of the International Strategy for Disaster Reduction

Van den Pol - van Dasselaar, A., van Beusichem, M., Oenema, O. (1999) Methane emissions from wet grasslands on peat soils in a nature preserve. *Biogeochemistry* 44: 205-220.

Vögele, S. Markewitz, P. (2008) Schätzung der Wassernachfrage großer Kraftwerke im Elbeeinzugsgebiet. In: Wirkungen des globalen Wandels auf den Wasserkreislauf im Elbegebiet – Risiken und Optionen. Schlussbericht zum BMBF Vorhaben GLOWA Elbe II, Kapitel 2.6

Vögele, S. Markewitz, P. (2008) Schätzung der Wassernachfrage großer Kraftwerke im Elbeeinzugsgebiet. In: Wirkungen des globalen Wandels auf den Wasserkreislauf im Elbegebiet – Risiken und Optionen. Schlussbericht zum BMBF Vorhaben GLOWA Elbe II, Kapitel 2

Ward, F.A. (1987): Economics of water allocation to instream uses in a fully appropriated river basin: evidence from a New Mexico wild river. *Water Resource Research*. 23(3):381-392

Ward, F.A., J.F. Booker A.M. Michelsen (2006): Integrated Economic, Hydrologic and Institutional Analysis of Policy Responses to Mitigate Drought Impacts in the Rio Grande Basin. *Journal of Water Resources Planning and Management*

Young, R. (2005): Determining the economic value of water. *Resources for the Future*. Washington.

Zebisch, M.; Grothmann, T.; Schröter, D.; Hasse, C.; Fritsch, U.; Cramer, W. (2005) Klimawandel in Deutschland. Vulnerabilität und Anpassungsstrategien klimasensitiver Systeme, UBA Climate Change 08-05 Berlin